230 AG

Technical Report

CEAC-TR-98-0105

A PRELIMINARY DESIGN STUDY OF COMPOSITE FLARE BOOM

Antonio Miravete

CEAC

APRIL 1998

COMPOSITES ENGINEERING AND APPLICATIONS CENTER
FOR PETROLEUM EXPLORATION AND PRODUCTION

UNIVERSITY OF HOUSTON
HOUSTON, TX 77204-0900

230 G

Technical Report CEAC-TR-98-0105

A PRELIMINARY DESIGN STUDY OF COMPOSITE FLARE BOOM

SUMMARY REPORT

Antonio Miravete

April 1998

**Composites Engineering and Applications Center (CEAC)
for Petroleum Exploration and Production
University of Houston
Houston, TX 77204-0903**

This document is intended only for the use of CEAC at the University of Houston, its industrial and government sponsors, and desgnated project participants. Any other use is not permitted.

INDEX

1. INTRODUCTION

Whether an offshore platform is designed for oil and gas, and even though the gas is being utilized by sale or reinjection, provision must be made for its disposal during startup, shutdown, some maintenance situations, and emergencies.

During these periods, the gas is transported to a safe distance from the platform before being burned. The vent line may be supported by one or more end supported trusses or a single truss cantilever supported from the platform itself. A specially designed burner tip and pilot will be installed on the end of the vent line.

The selection of the vent line support system involves a coordination of both economic and operational criteria. The cantilevered flare boom will cost less than the other alternatives up to the point that the weight and wind induced moments of the cantilever begin to be reflected significantly in the primary platform design. This point is primarily a function of the cantilever length. For most present applications the limit lies between 100 feet and 250 feet in the horizontal projection.

The primary operational limitation to the volume of gas burned from a cantilever supported flare is the maximum radiant flux which can be allowed to fall on the platform. A maximum of 440 BTU per hour-square foot from combined sun and flare is generally accepted as a conservative design criteria.

The need to make the flare boom very lightweight for its overall size and to allow a single lift installation has produced a fairly complex structure to inspect and maintain, due to the fact that steel is a very heavy material.

The poor weld quality, the low fatigue strength of steel and the need to design large metallic surfaces (with the correspondent increase of wind loads), have led to failures, fatigue crackings and expensive maintenance operations.

One alternative which is innovative and efficient in terms of weight, cost, mechanical behavior and maintenance, consists of implementing composite materials.

Designing a flare boom with organic-matrix composite materials can be considered a challenge. The list of disadvantages and advantages of this material system compared to the standard one used in current flare booms, which is carbon steel, are the following:

Table 1.1 Disadvantages and advantages of organic matrix composite materials with respect to the steel

Disadvantages of organic-matrix composite materials compared to carbon steel	Advantages of organic-matrix composite materials compared to carbon steel
■ Higher cost of raw materials	■ Higher Mechanical Strength
■ Lower High Temperature Resistance	■ Lower Maintenance Costs
■ Lower Stiffness	■ Lightweight structure
■ More difficult to perform joints: welding is not possible	■ Molding Manufacturing Processes

It is obvious that the cost of the composite flare boom must be competitive with the standard carbon steel. This is definitively one of the toughest requirements since the cost of the raw materials in this last case is very low. All carbon steel flare booms must be painted or coated due to the limitations of metallic materials (corrosion and high temperature resistance). According to the data available, the aluminum coating, which is considered as one of the most efficient coating in terms of maintenance and price, increases the cost about 30%.

The high temperature resistance is also another key issue. Several methods are proposed to meet this requirement. Ceramic coating is a promising alternative since it is very efficient in terms of heat isolation and the cost is very low, as long as this coating is not designed to bear any mechanical load. Along this preliminary report, the organic matrix composite material structure will bear the mechanical load. Only the platform, located on the top of the flare boom will be designed with metallic materials due to the fact that the temperatures are extremely high in this area.

The stiffness is a critical factor in terms of mechanical behavior, since low cost organic matrix composite materials are several times less stiff that carbon steel. In order to overcome this problem, an optimization process will be carried out: the geometry of the flare, the material system, the typology of the material used for the chord wall, and finally the joints will be optimized in terms of cost and mechanical requirements. Needless to say the analysis must be very accurate and that design and manufacturing must be totally compatible, feasibility being an important matter in this project.

Finally, it is important to emphasize that a successful design of a composite flare boom in terms of cost and thermal and mechanical requirements would imply not only a reduction of the topside structure mass, but also a new concept of cranes and other primary structures in the topside part of an offshore construction, with the correspondent advantages of massive reduction of weight in such an important area.

2. DESCRIPTION OF THE STRATEGY: ECONOMICAL ASPECTS

The target of this work is to design a composite flare boom that is competitive with carbon steel flare boom from both points of view: economical and thermo-mechanical behavior.

Basically, the material system used in this preliminary study is E-glass/polyester resin. A small amount of carbon fiber will be used in order to increase the stiffness and the fatigue strength in critical areas. Since this material will be used in a very small proportion, it will not mean a significant increase in the final cost of the boom.

The cost of a standard carbon steel material for a flare boom application is the following:

Raw Material Cost:	1$/lb
Finished Material Cost:	2$/lb
Aluminum Coating:	10$/ft^2

A standard chord thickness is 0.3 in (0.025 ft), thus the coating cost is 400 $/ft^3.

Since the carbon steel density is 500 lb/ft^3, the coating cost will be: 0.8$/lb

Thus, the total finished material cost including raw materials, assembly, welding and coating is: **2.8 $/lb**.

The strategy followed in this preliminary report is the following:

1) The composite flare boom shape geometry will be optimized in order to take advantage of the possibilities of the molding processes.

2) Regarding the boom composite cross section, tubular shapes will be used, in order to reduce the wind loads. Initially we will work with 3 chord structures, though 4 chord structures can also be designed following the same philosophy. According to the present study, the composite flare boom will have the same diameter and the same thickness as the standard carbon steel. Therefore, the volume of the chord using composite materials will be the same as the standard carbon steel flare boom.

3) The diagonal braces will be suppressed. One key advantage of composite materials deals with the molding manufacturing processes. By means of a proper design and the adequate manufacturing technologies, the joints between chords and transverse braces will be stiff and strong enough to transmit the shear stresses through the transverse braces. The degree of translation will be suppressed by triangularizing the flare, as it will be explained later. The suppression of diagonal braces is a key concept in this design, since their exposition surface to winds is about 40% of the total surface.

4) The distance between chords will be increased by 40%, in order to increase the boom cross section inertia. Therefore the length of the transverse braces will be increased also by 40%.

5) The balance on weight saving is the following:

   - The chord weight corresponds to 48% of the total boom weight. Since the volume for both designs – composite and carbon steel – is the same and the composite material density is four times less than carbon steel, the composite structure weight is 25% of the standard carbon steel boom (75% of weight saving), and the weight percentage will change from 48% to 12%.
   - The diagonal braces, whose weight is about 35%, are eliminated.
   - The transverse braces weight is 16% of the total boom weight. Since the volume for the composite designs is 40% higher that the carbon steel and the composite material density is four times less than carbon steel, the composite structure weight is 16% X 1.4 X 0.25 = 5.6%.
   - Therefore, the weight of the composite flare boom in terms of percentage is: 12%+0%+5.6%=17.6%. In other words: the weight of the carbon steel flare boom is 5.68 times higher than the composite and **the final weight saving is: 83.4%**

6) In order to be competitive in terms of cost with the standard carbon steel flare boom, the targeted cost is 2.8 $/ lb. x 5.68= **15.9 $/lb.**

In other words, if the weight of a standard flare boom for an offshore structure in the Gulf of Mexico were 70,000 lb., the composite structure would weight 12,324 lb. The weight reduction would be 57,676 lb.

By reducing the flare boom structure weight almost six times, other important advantages will be obtained:

- Manipulation of Materials
- Assembly
- Transportation
- Installation
- Reduction of topside structure weight
- Reduction of the weight of other structures below the flare boom.

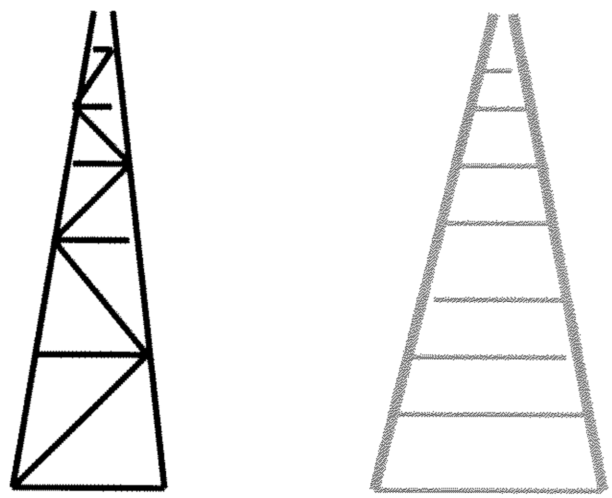


Figure 2.1 Flare Boom Plan. Design on carbon steel (black). Design on composite materials (yellow).

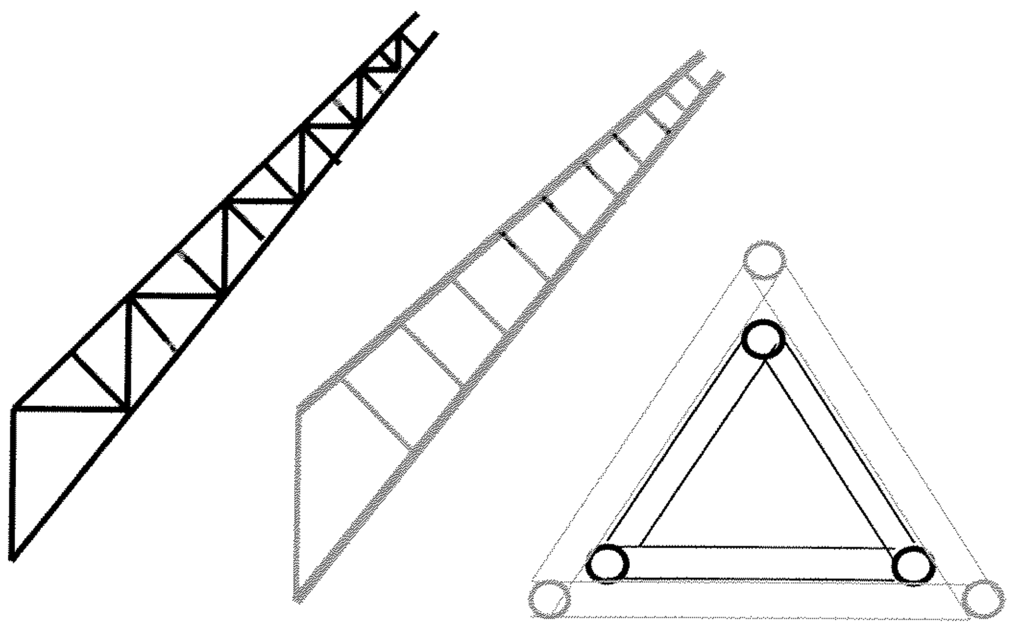


Figure 2.2 Flare Boom Elevation (left) and cross section (right). Design on carbon steel (black). Design on composite materials (yellow).

3. MANUFACTURING

The manufacturing process is a key issue in the design of the composite flare boom. Designing with steel does not present any problem in terms of manufacturing processes since cutting and welding carbon steel profiles is simple, efficient and cheap.

The manufacturing process in our case must be selected in terms of:

- Feasibility
- Cost
- Mechanical Requirements

According to the list shown above, the following manufacturing processes will be analyzed:

- Pultrusion
- Filament Winding
- Resin transfer Processes
- Others

3.1 PULTRUSION

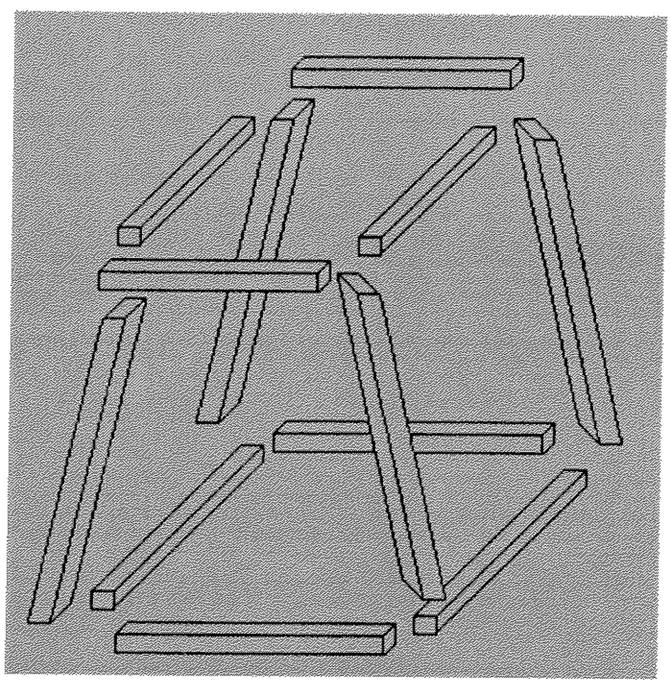


Figure 3.1 Scheme of a boom modulus manufactured by pultrusion.

The advantages of this design are:

- High Stiffness and Strength
- Cheap Manufacturing Technique
- Reliable Manufacturing Technique

A major disadvantage is the definition of the joints. Recently several structures have been presented for construction designed by using pultruded profiles. The joints are solved by means of nodes.

In our case, high loads exist in the intersection between the chords and the transverse profiles. A very stiff and strong joint is required in order to meet the stiffness and strength requirements.

Pultruded profiles might be used in addition to other pieces made by means of other manufacturing processes.

Figure 3.1 shows a preliminary design of a modular composite flare boom consisting of a pultruded structure.

3.2 FILAMENT WINDING

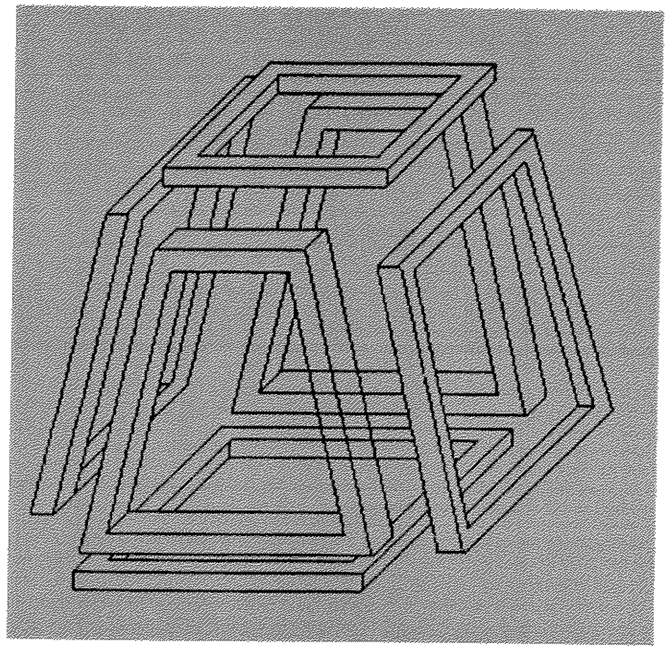


Figure 3.2 Scheme of a boom modulus manufactured by frames made of filament winding.

A preliminary design of a modular composite flare boom based on wounded composite frames is represented in Annex II. This technique is being used in Europe for high structural applications. The manufacturing process is filament winding.

The major advantages of this design are

- High Stiffness and Strength of the beams of the frame (mechanical properties similar to the pultruded beams)
- High Stiffness and Strength of the joints due to the fact that fibers are continuous along the perimeter of the frame.

A mayor disadvantage is the complexity of the process, since this composite frame cannot be manufactured by using a standard filament winding machine. Several improvements must be in a standard filament winding machine made in order to appropriately process this type of configuration.

3.3. RESIN TRANSFER PROCESSES

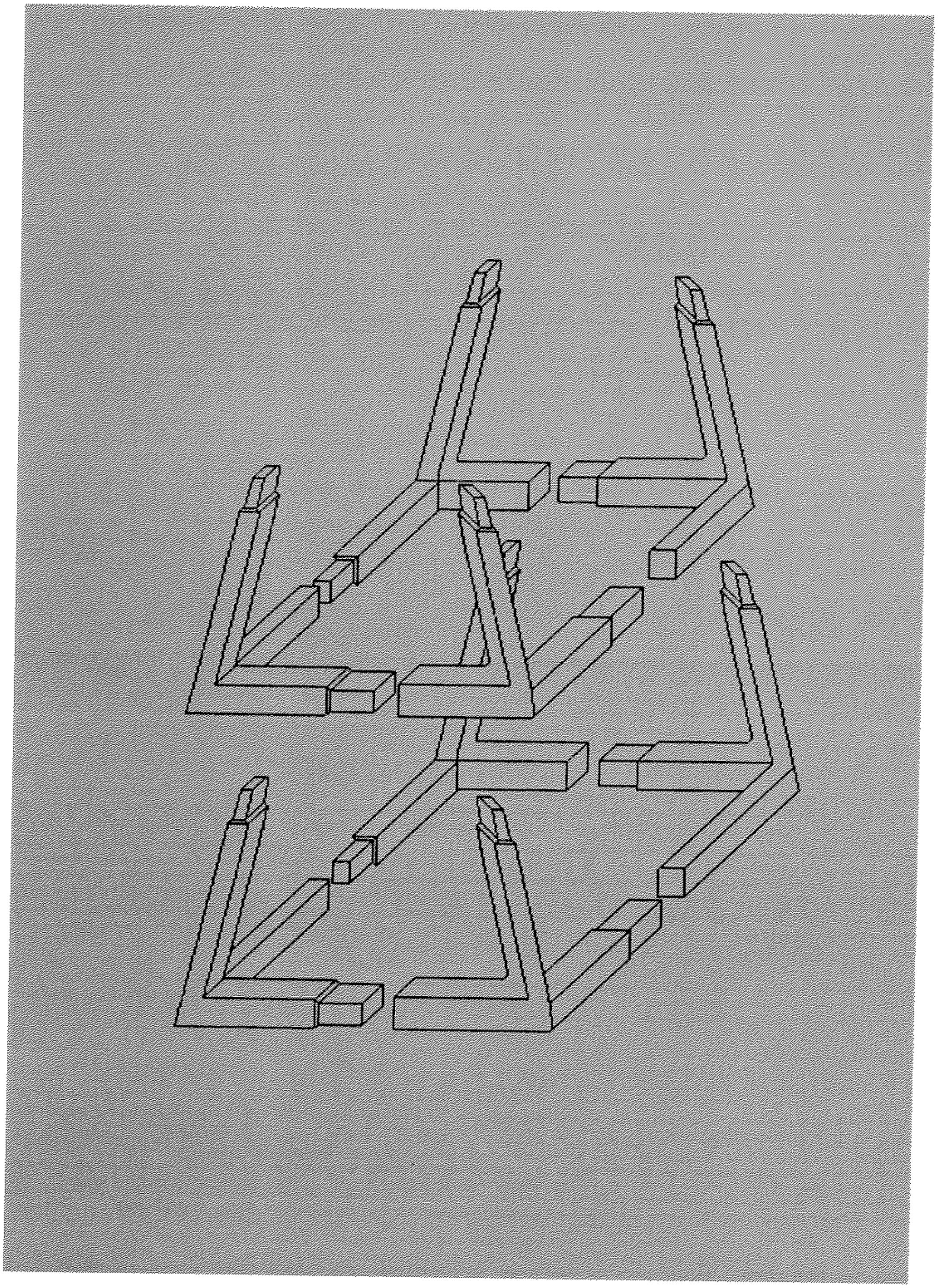


Figure 3.3 Scheme of a boom modulus manufactured by pieces made of resin transfer molding.

Figure 3.3 represents a preliminary design of a modular composite flare boom based on moduli manufactured by Resin Transfer Molding (R.T.M.).

The major advantages of this design are:

- High Stiffness and Strength of the beams of the frame (mechanical properties similar to the pultruded beams)

- High Stiffness and Strength of the joints due to the fact that the whole modulus, including beams and joints, is manufactured in just one shot (R.T.M. process).

- R.T.M. process has been used for the last decades worldwide, the results for structural applications being nowadays outstanding from both points of view: cost and mechanical properties.

3.4 OTHERS

An interesting manufacturing process for the composite flare boom consists of combining the resin transfer technology and pultrusion:

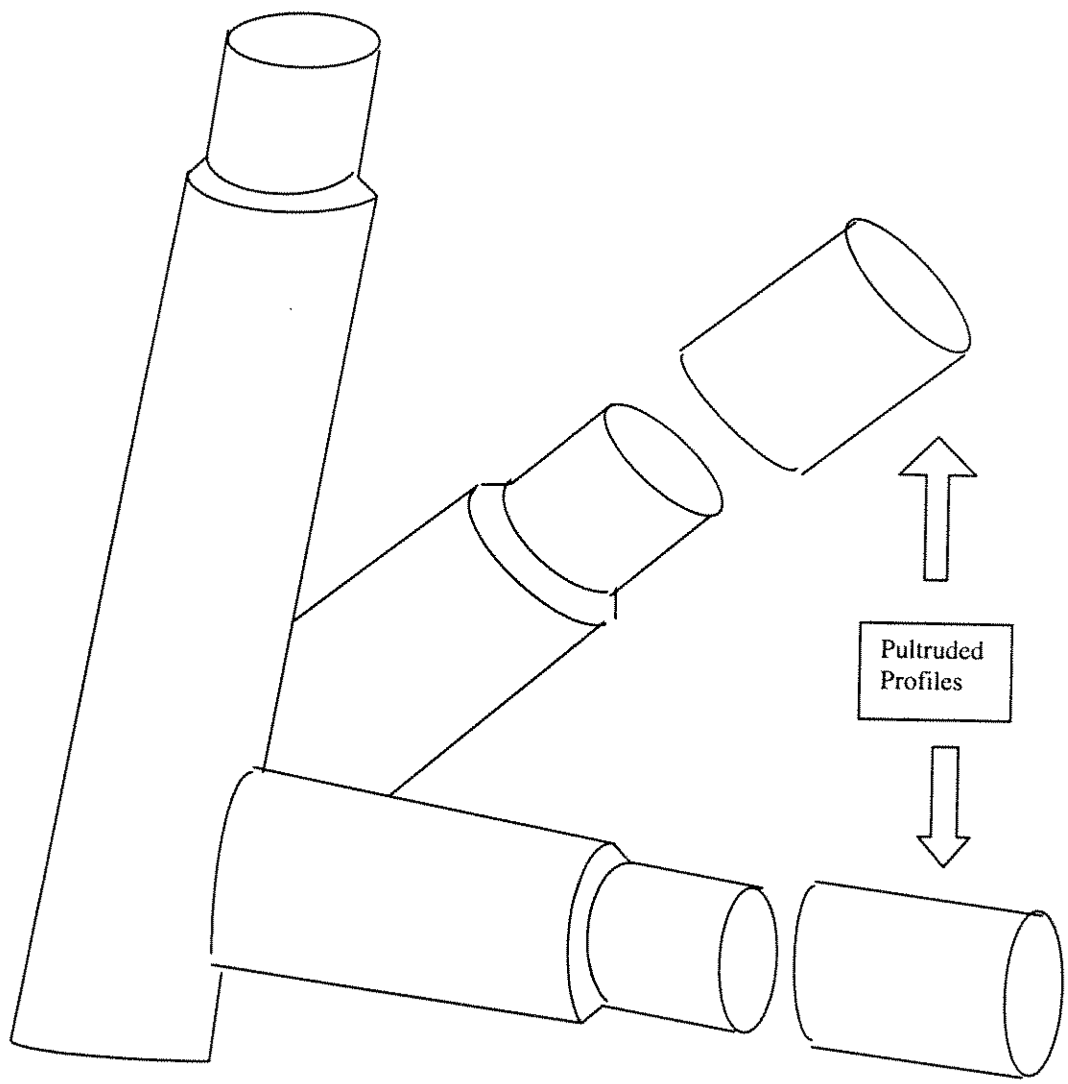


Figure 3.4 Detail of a modulus made by means of a combined manufacturing process: resin transfer molding and pultrusion

The scheme shown in Figure 3.4 represents a modulus made by means of resin transfer molding and two pultruded profiles.

The whole composite flare boom could be made by using one mould, since this piece can be assembled to another two or three to make a 3 or 4 chord composite flare boom.

Also, by means of this procedure, it is possible to make a composite flare boom whose width and height vary along the boom. The maximum width and height section will be located at the bottom, where the stresses are high, and the minimum width and height section will be located at the top, where the boom is connected to the tip.

The variable width and height are obtained by using pultruded profiles whose length is variable: To assembly the flare boom section at the bottom, long pultruded profiles will be used and shorter profiles will be included for upper sections.

The connections between the resin transfer pieces will be carried out by means of bonded joints. The bonded surface will be sized in order to meet the stiffness and strength requirements.

The joints between the resin transfer molding and the pultruded beams will also be made by means of bonded joints.

The critical areas are the intersections between the chords and the transverse beams. This sections will be made entirely by means of resin transfer molding. The thickness and the orientation of the fibers will be optimized, such that the static and fatigue strengths will be appropriate for the current design. The joints between the RTM piece and the pultruded beams are carried out in areas where the stress gradients are low.

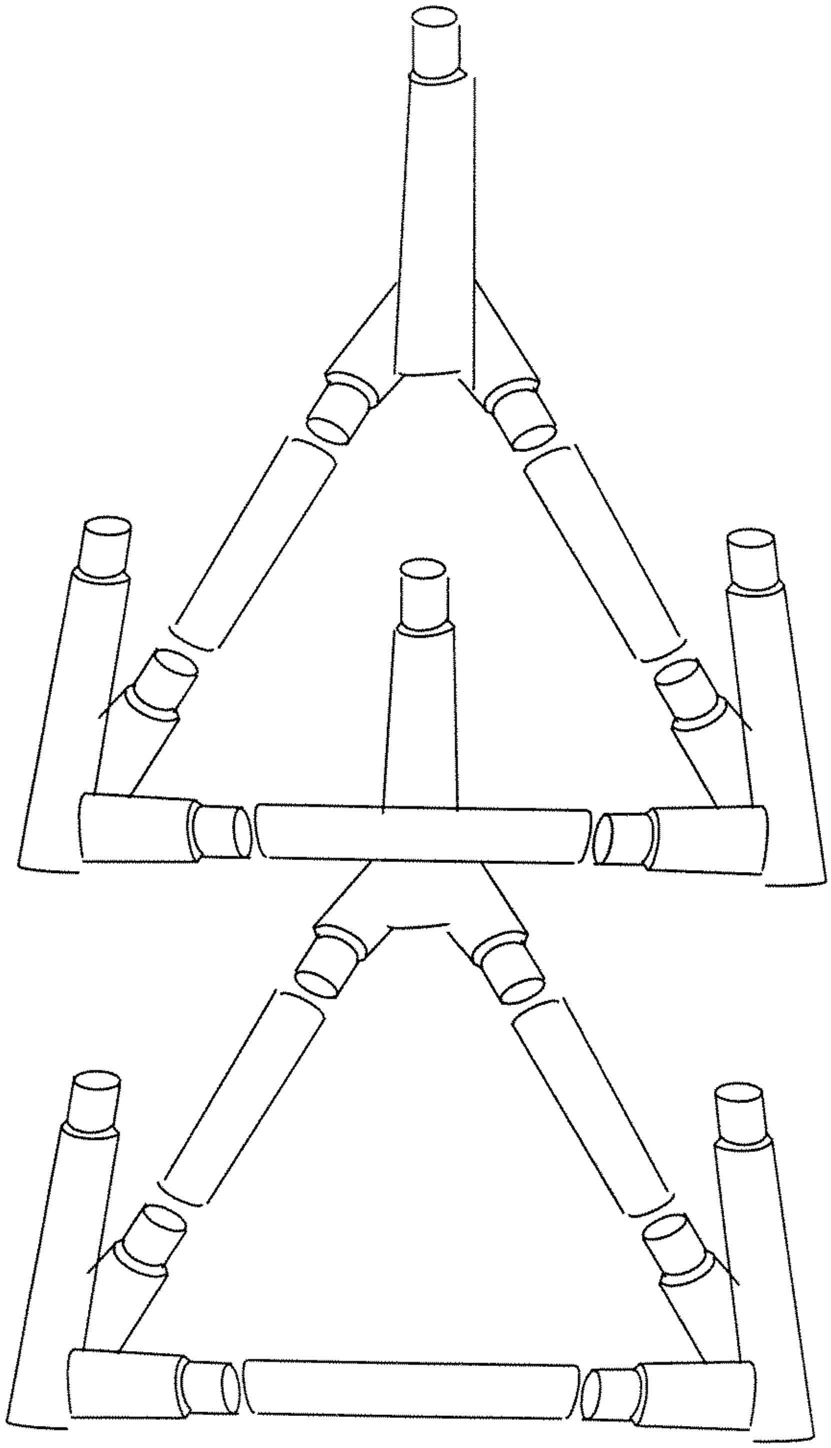


Figure 3.5 Scheme of the assembly of the composite flare boom

4. DESIGN PRINCIPLES

According to the advantages and disadvantages of organic-matrix composite materials compared to carbon steel, mentioned above, the following aspects must be studied:

- High Temperature Resistance
- Shape Optimization
- Stiffness
- Global Boom Buckling
- Chord Buckling
- Design of the chord

4.1 HIGH TEMPERATURE RESISTANCE

To determine the high temperature resistance, the first goal is to achieve the temperature profile.

The temperature profile is obtained by means of the radiation formulation, since heat conduction and convection are less relevant. However, it could be interesting to assess heat conduction on both systems: steel and composite materials, since the balance will be favorable for the latter.

4.1.1. Radiation Formulation

Thermal radiation is energy emitted by matter at a finite temperature as a result of changes in the electron configurations of the atoms or molecules. Generally, radiation heat transfer analysis is focused on solid surfaces but emission may also occur from liquids and gases. Radiation energy is transported by electromagnetic waves or photons. Unlike conduction and convection, radiation does not require the presence of a medium to propagate. Actually, radiation transfers heat energy most efficiently in a vacuum.

The radiative heat flux emitted by a real surface is giving by the following equation:

$$q'' = \varepsilon \, \sigma \, Ts \tag{4.1}$$

where:

q'' = heat flux (W/m2)
ε = emissivity constant
σ = Stefan-Boltzmann constant = 5.67 x 10E-8 w/m^2K^4
Ts = surface temperature (K)

ε is the radiative property of a surface whose value is in the range $0 < \varepsilon < 1$. The surface emissivity indicates how efficiently the surface emits radiative energy relative to an ideal radiator or blackbody ($\varepsilon = 1.0$). Just as surfaces emit energy, another surface can absorb·

a portion of that energy. The rate of energy absorbed per unit surface area can be defined as:

$$q''_{abs} = \alpha q'' \tag{4.2}$$

where α is the absorptivity constant. α is the radiative property of a surface whose value is in the range $0 < \alpha < 1$. In contrast to radiation emission which reduces the thermal energy of matter, absorption increases thermal energy.

To determine the net rate of radiation between two or more surfaces requires a finite element analysis.. Properties of the surfaces, geometry distributions,.their orientations, and other factors must be considered. For our case we will focus on a simple case that involves the net radiative exchange between a surface and a much larger surface that completely surrounds the smaller one. The surface and its surroundings are separated by a medium that has no effect on the radiation transfer. The net rate of radiative heat flux between the surface and the surroundings can defined as:

$$q'' = \sigma\ (\varepsilon\ T_s^4 - \alpha\, T_{sur}^4) \tag{4.3}$$

where:

T_{sur} = temperature of the surroundings

This formula can be applied for the flare boom case study.

4.1.2 Determination of the Temperature Profile

The sensitivity constant is obtained by the formula:

$$\varepsilon = (4\ \pi\ R^2\ q'')/(Q\ C\ S) \tag{4.4}$$

Where:

R: Distance from the center of radiance
Q: Gas rate
C: Calorific Value
S: Shape or view factor

The absorptivity constant depends of the coating system of the flare boom.

To perform an accurate study of temperature profiles, a thermal finite element study must be done to assess the shape of view factor. Once S is known, the value of the sensitivity constant can be determined by applying Eq. (4.4).

Supposing that both constants :

$\varepsilon = \alpha = 1$

The following formula can be applied:

$$q'' = \sigma \ (T_s^4 - T_{sur}^4) \quad (4.5)$$

For a standard flare boom (150 feet long), the maximum radiation on the platform deck is:

$q''_{bottom} = 440$ Btu/ ft^2 hr

According to the information available, the center of radiation is located at 70 feet of the boom top and q" is inversely proportional to the distance from center of radiation:

$q''_{top} = [(70+150)/70]\ q''_{bottom} = 1{,}382$ Btu/ ft^2 hr

The net rate of radiative heat flux is:

1,382-440=942 Btu/ ft^2 hr

In SI units:

942 Btu/ ft^2 hr = 2,970 w/m^2.

Thus,

2,970 w/m^2.= 1 X 5.67 x 10E-8 W/m^{2}K^4 X $(T_s^4 - T_{sur}^4)$

Estimating T on the deck :

T_{sur} = 100 F = 310K

T_s = 498K = 437F

In the middle of the boom:

q''_{top} = 911 Btu/ ft^2 hr

The net rate of radiative heat flux is:

1,382-911=471 Btu/ ft^2 hr

In SI units:

471 Btu/ ft^2 hr = 1,439 w/m^2.

Thus,

$1{,}439\ w/m^2 = 1 \times 5.67 \times 10E\text{-}8\ W/m^2K^4 \times (T_s^4 - T_{sur}^4)$

T on the boom top is:

$T_s = 437F = 498K$

And:

$T_{sur} = 435K = 325F$

Once temperatures at the top, middle and bottom of the boom are known, an estimated temperature profile can be plotted (Figure 4.1):

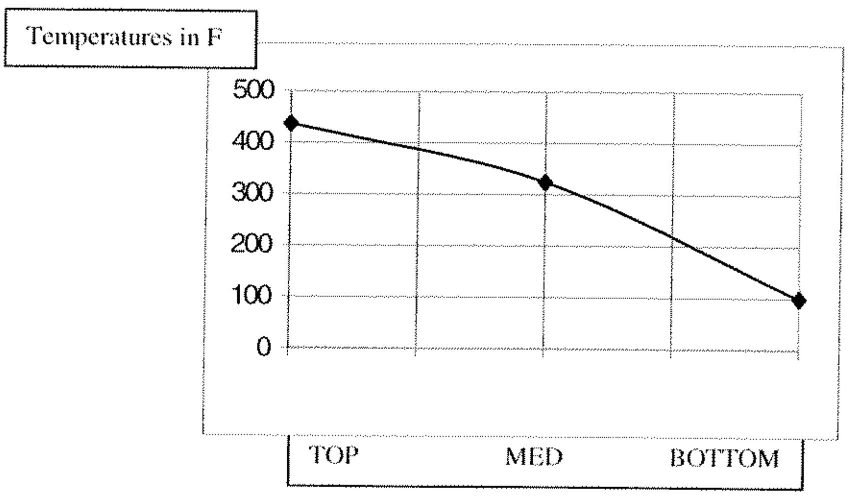


Figure 4.1 Estimated Temperature Profile.

This profile coincides with information received on standard flare booms, showing that the temperature at the top of the flare never gets above 450F.

Organic matrix composite materials can bear these temperatures by means of a suitable ceramic coating. Nowadays, there are commercial ceramic coating that are applicable to organic matrix composite materials.

There are also several options to design the composite flare boom in terms of high temperature resistance.

- To use a metallic structure near the tip
- To use high temperature matrices.

Depending of the final design, the best option will be selected. In principle, a combination of the first two options looks the optimum solution since high temperature matrices are very expensive.

4. 2 SHAPE OPTIMIZATION

Curved steel pieces are much more difficult to manufacture and therefore, more expensive than linear. Since composite materials are manufactured by means of molding processes, curved structures can be easily manufactured.

A finite element sensitivity study has been carried out in order to find out the optimum shape of a cantilever structure subjected to horizontal loads (wind loads) and vertical loads (weight of boom and tip).

Five cases have been studied: The linear structure that connects the platform and the flare tip and four curved boom with various curvatures (Figure 4.2)

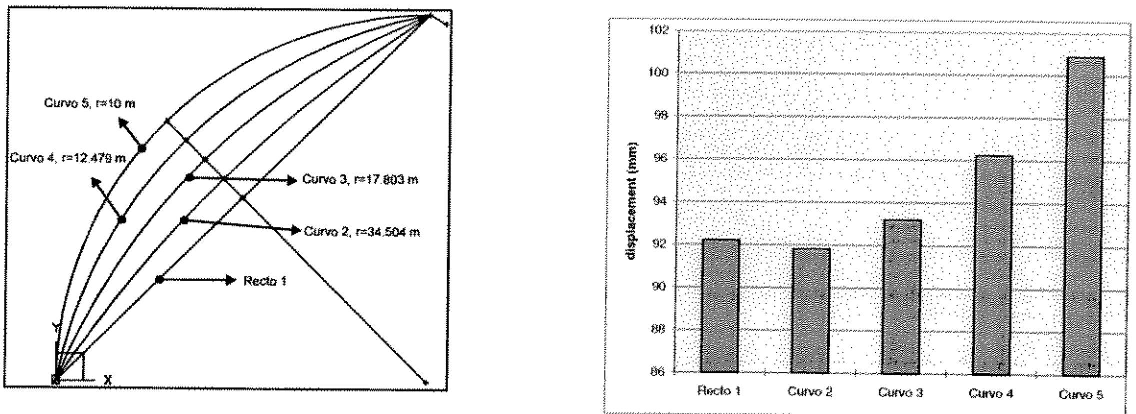


Figure 4.2 Results of the shape optimization

The flare boom comprises a main 140' long triangular tubular space frame boom cantilevered from the module support frame at an angle of 45 degrees.

The results show that the minimum deflection is obtained for a large curvature, very close to the linear boom. As the radius of curvature increases, the stiffness of the boom decreases.

Further analyses must be performed to find out if an optimum shape must be defined for a general flare boom geometry.

Since the optimum shape reported in this study is very close to the linear boom and curved structures would require a large number of moulds, and therefore a higher cost in terms of manufacturing, the linear geometry has been selected to be analyzed in this report.

However, other geometries different to angles of 45 degrees and boom compositions should be studied since the shape represented in Figure 4.3 must be manufactured by using composite materials:

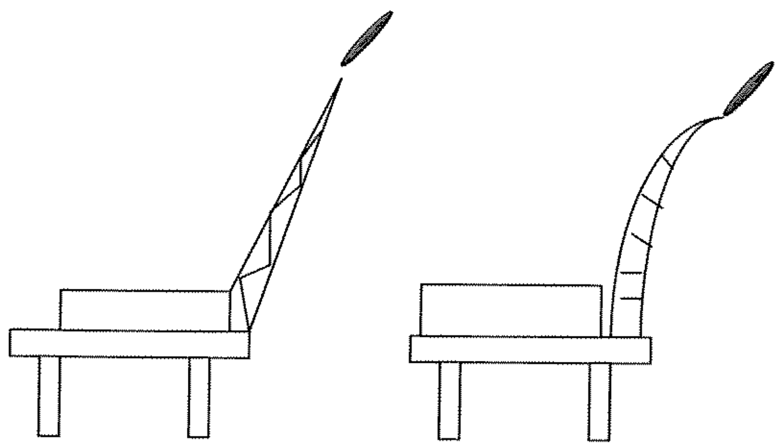


Figure 4.3 Standard flare boom (left) and Curved composite flare boom (right).

4.3 STIFFNESS

The current design consists of three chords manufactured by resin transfer technologies. The material system for the chords will be a hybrid material, whose composition will vary along the boom. The top third of the boom will be 100% fiberglass/polyester resin. The third part at the middle will have a 67% of fiberglass and 33% of carbon fiber. Finally, the third part at the bottom, will be made up of 67% of carbon fiber and 33% of fiberglass, since this is the area where stresses are higher.

According to our experience on resin transfer techniques, this hybrid material presents a elastic modulus which is 2.5 five times less than steel. The percentage of fiber volume is 60%. Though 70% of fiber volume can be reached by using resin transfer technologies, fatigue failures have been reported for volume fractions higher than 60%.

The transverse braces will be made up of fiberglass and polyester resin.

The density of the E-glass/polyester resin system is four times less that of carbon steel. Since we are assuming that the volume of the composite flare boom will be the same as carbon steel, the weight of the composite structure will be four times less.

Since the height of the flare boom cross section is 1.4 times higher, the cross section inertia, will be double for the composite design, since the inertia is proportional to the square of the height.

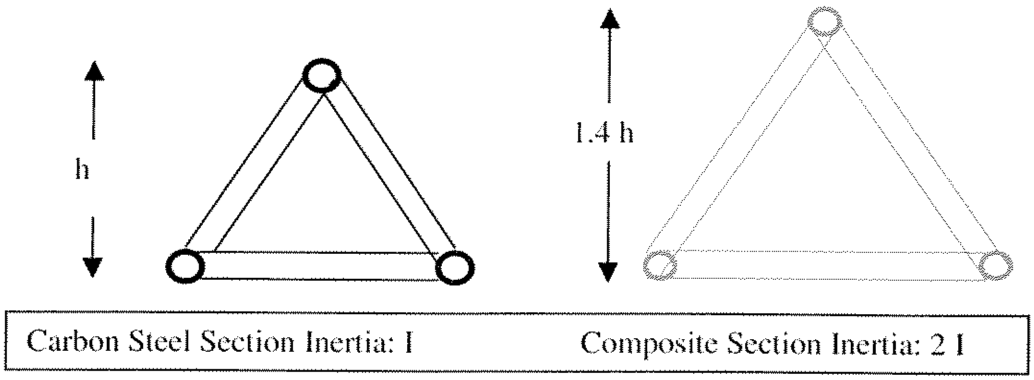


Figure 4.4. Comparison of cross sections of carbon steel and composite flare booms.

The EI factor will be 0.8 times less for the composites design with respect to that of carbon steel since the elasticity modulus E is 2.5 times higher for the carbon steel and I is 2 times higher for the composites design. In other words, the composite flare boom is 20% less stiff that the carbon steel.

Regarding the loads, there are two types:

- Horizontal loads: Wind load
- Vertical loads: Weight of the flare boom and Weight of the flare tip

According to the data available, as it was mentioned in Chapter 2, the suppression of diagonal braces means that the exposition surface to the wind is about 40% of the total surface. Therefore the horizontal load is the half the load that exists for the standard carbon steel flare boom. The increase of the transverse brace length only leads to a 5 % of the exposition surface to the wind. Therefore the surface reduction will be 40%-5%=35%, and the wind loads will be 2/3 that the standard boom design.

The vertical load is drastically reduced since the weight of the composite flare is 5.68 times less than the carbon steel. Considering that the flare tip is the same for both and that the platform must be made up of steel, the calculations are the following:

For a standard flare boom (150 feet long), the carbon steel structure weight is about 85,000 lb, the weight of the tip flare is estimated on about 5,000 lb, and the weight of the platform about 10.000 lb. In other words the weight of the carbon steel structure corresponds to 82.4%. If this part is substituted by a composite structure whose weight is 5.68 times less, the reduction of load is:

82.4% / 5.68 + 17.6% = 32.1%.

Therefore the vertical load is reduced three times.

Since the horizontal load (wind) is about 2/3 and the horizontal load (weight) is about 1/3 compared to the steel flare boom, it can be concluded that the total load is about 2/3 of the one that withstands the steel flare boom from a conservative point of view. According to the data available, the value of the weight of the carbon steel flare boom is higher that the total wind load.

The composite flare boom described in this report, in operation, will present a deflection lower that the standard carbon steel: the static stiffness of the composite flare boom is about 80%, the forces are 66% that the carbon steel. In conclusion, the deflection would be 21% less for the composite design and in other words, this system will be 21% stiffer than the standard flare boom in static conditions.

4.4 GLOBAL BOOM BUCKLING

The weight of the tip and the boom and the wind loads will generate compression in the global structure:

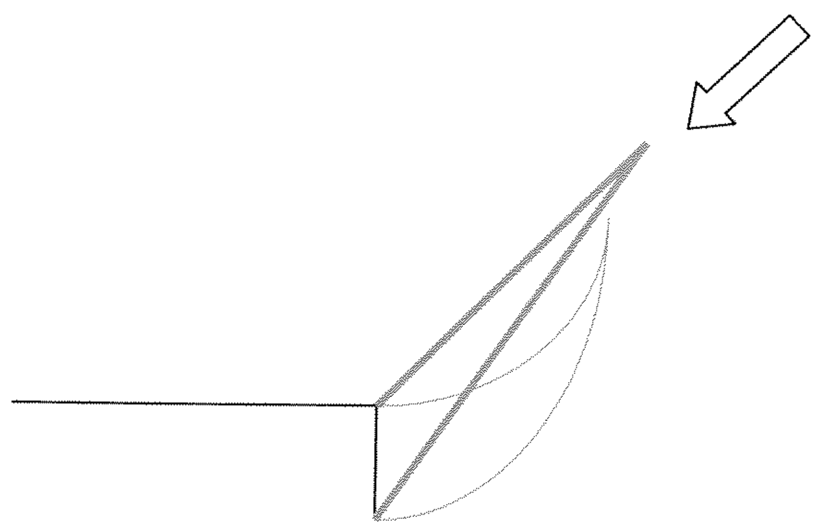


Figure 4.5 Global boom buckling deformation.

As it has been demonstrated above, the compression force will be 0.66 of the carbon steel. Also, the section inertia is the double of the carbon steel since the height of the section has been increased 1.4 times. Therefore the total factor from the force reduction and the height increase is 3. Since the elasticity modulus of the composite material is about 2.5 times less that the carbon steel, it can be concluded that the global boom buckling resistance is higher that the standard carbon steel flare boom.

4.5 CHORD BUCKLING

The flare boom is subjected to horizontal and vertical loads. These loads, apart from generating a compression force, also lead to a bending of the boom (Figure 4.6):

The bending forces generate a tension stress on the top chord and compression stress on the two bottom chords. To avoid buckling on these two bottom chords, the distance between two consecutive transverse braces must be calculated. The formula that controls the chord buckling is

$$Nx = \pi^2 E I / 12 L^2$$

Where L is the distance between two consecutive transverse braces.

Since the load for the composite flare boom is 0.66 that the carbon steel and the distance between chord is 1.4 times higher, the compression load will be: 1.5 x 1.4 = 2.1 times lower than for the carbon steel flare boom. Since the elasticity modulus is about 2.5 times lower, the distance between two consecutive transverse braces must be:

$$(2.5/2.1)^{1/2} = 1.09$$

In other words, 1.09 times lower than the critical distance for carbon steel. According to the data available, the distance between two consecutive transverse braces in a standard carbon steel boom is higher than the critical, and therefore, it will not be necessary to increase the number of transverse braces.

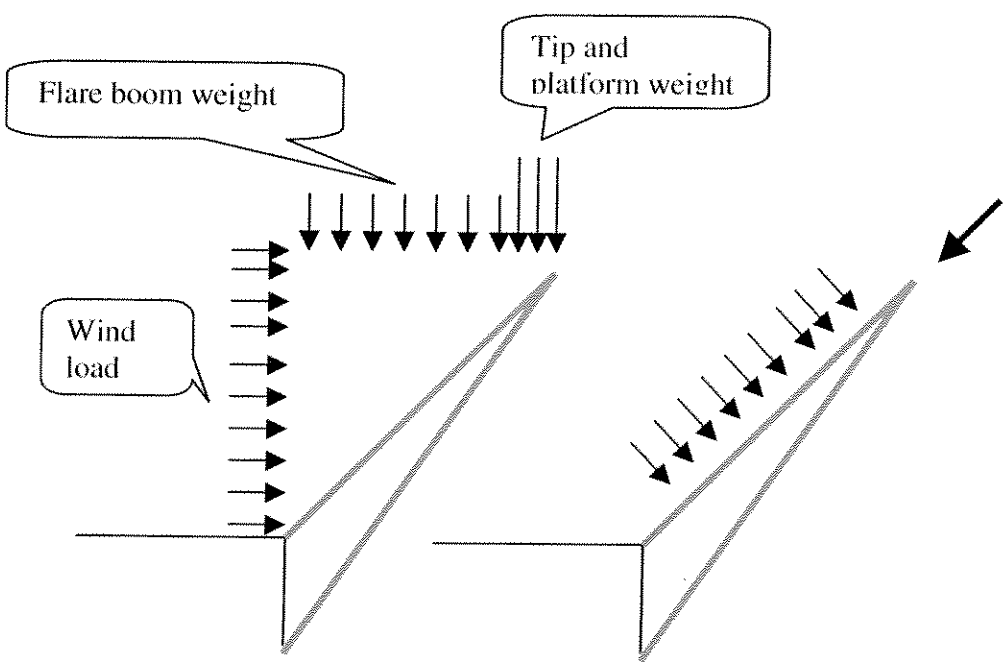


Figure 4.6 Forces of bending and compression over the flare boom.

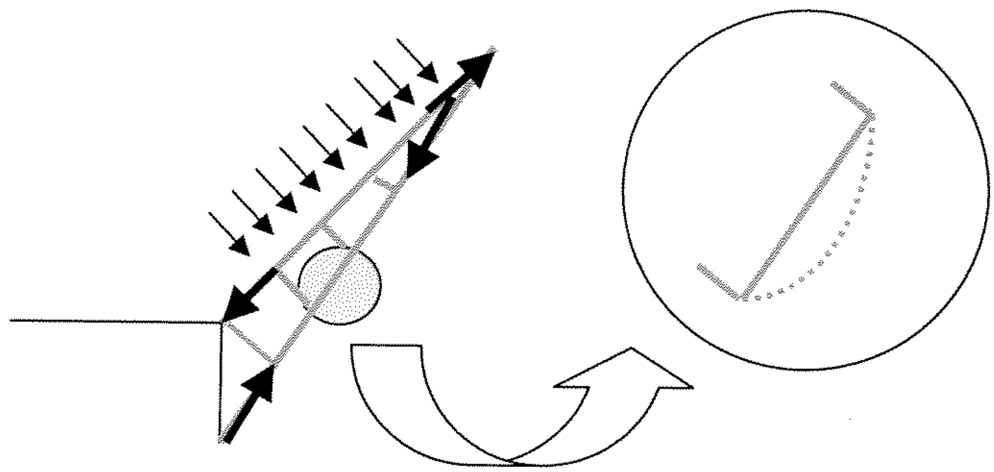


Figure 4.7 Chord Buckling Deformation.

4.6 DESIGN OF THE CHORD

There are several ways to design the chord. In all the cases, the chord must be feasible in terms of manufacturing.

Resin transfer molding or scrimp process are very promising candidates for this type of structures. High fraction volumes can be reached (60%), and therefore, the final structure will present appropriate elastic moduli and strength for the current design.

A mould is needed to manufacture a certain piece by a resin transfer process. Since cost is a key issue, the number of moulds to be made must be reduced at maximum.

Let us suppose that the whole flare boom can be made by using just one mould. In such a case, the cost is highly reduced but we pay a penalty: flexibility. All the pieces that compose the chord will have the same thickness. We can vary the thickness along one piece; we can have a thicker structure at the bottom of each piece and a thinner wall at the top, but this will be the same for all the substructures.

At the tip of the flare, there are only forces related to the tip flare weight. The cross sections below the tip will be subjected to the boom weight and wind loads and these loads will be increasing along the boom. The area most loaded will be the bottom of the structure: this cross section will be subjected to the bending moment due to the total flare boom weight and the wind loads. Also, there will be a compression load. Since the loads are increasing from the top to the bottom and the thickness of each modulus will not vary, the configuration and the material system will be properly optimized along the boom:

The following typologies are available:

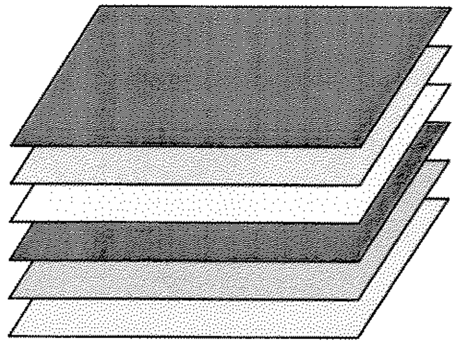


Figure 4.8. Scheme of a solid Laminate.

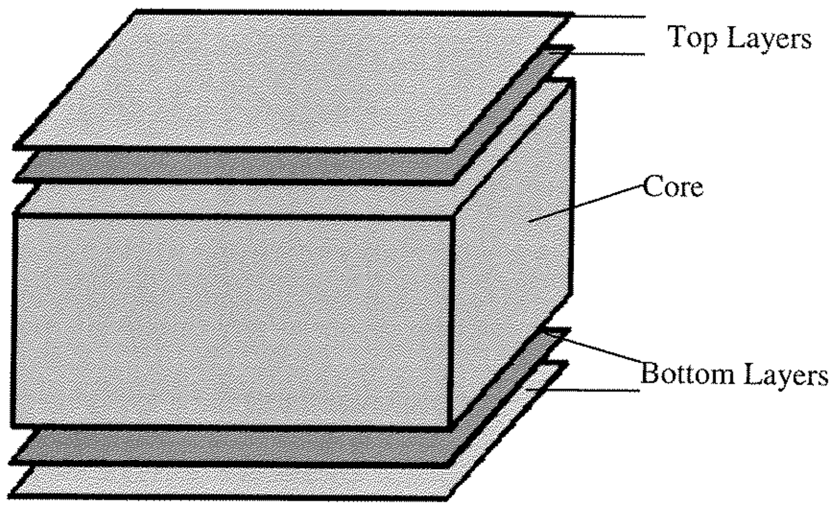


Figure 4.9. Scheme of a sandwich structure.

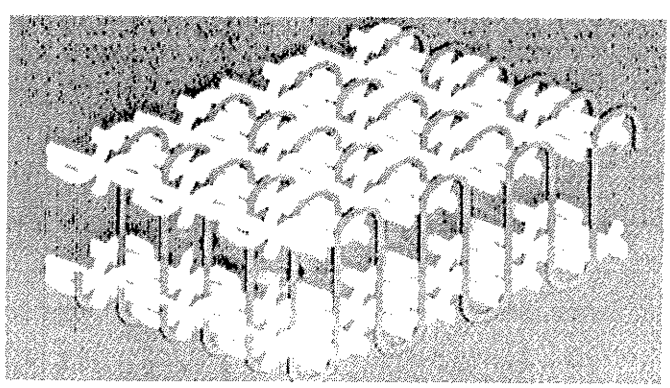
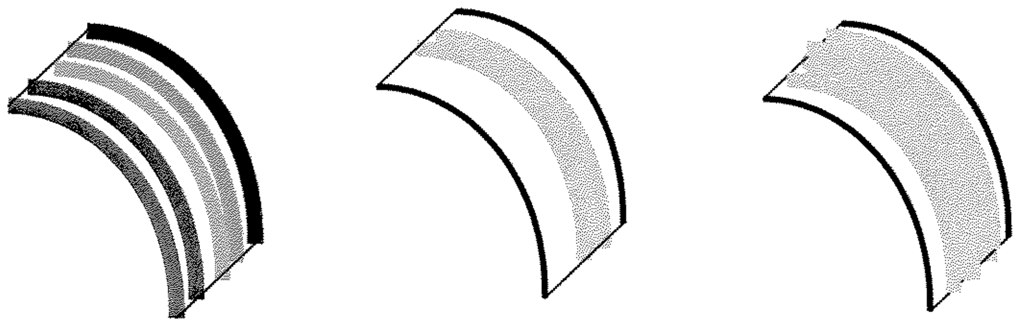


Figure 4.10. Scheme of a 3D fabric sandwich structure.

In those areas where high stresses are reported – at the bottom of the boom -, a solid laminate is definitely the optimum configuration, since the whole thickness is used as a structural wall.

When stresses are lower –at areas above the bottom- , the weight will be reduced by using sandwich structures. The core will occupy a part of the wall. The higher we get up the boom , the thicker the core must be, since for higher parts – near the tip- the stress level will be lower and therefore the structural thickness will decrease:



Bottom area Solid laminate	Medium area Sandwich with thin core	Top area Sandwich with thick core

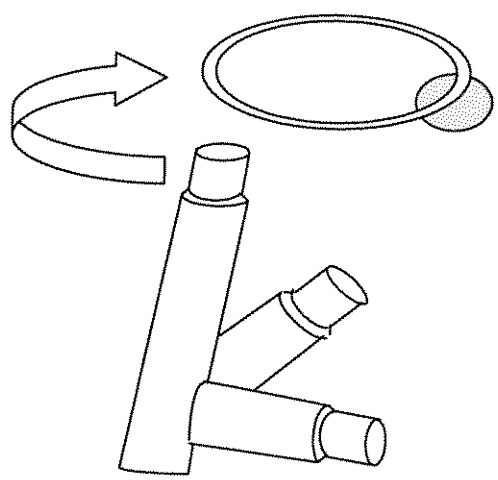


Figure 4.11 Typologies used in the chord wall along the boom.

Another typology available consists of the 3D fabric sandwich structure. The most relevant aspect of this configuration is that the skins are connected through the sandwich thickness by means of piles. This fact makes that the shear and peeling strength are higher that for standard sandwich structures.

In those areas where interlaminar and normal stresses are high, this configuration is recommended.

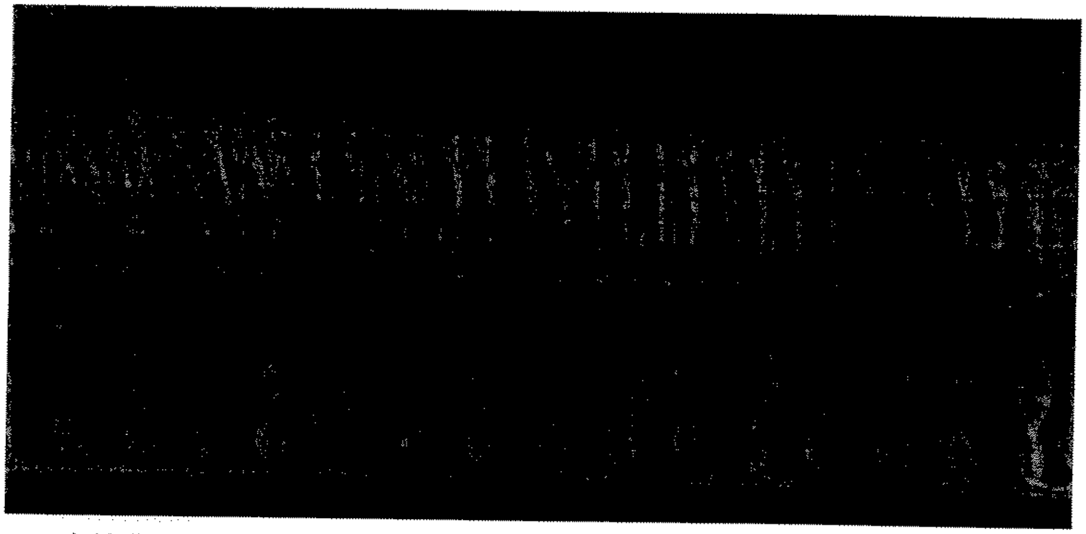


Figure 4.12 Detail of a 3D fabric sandwich structure.

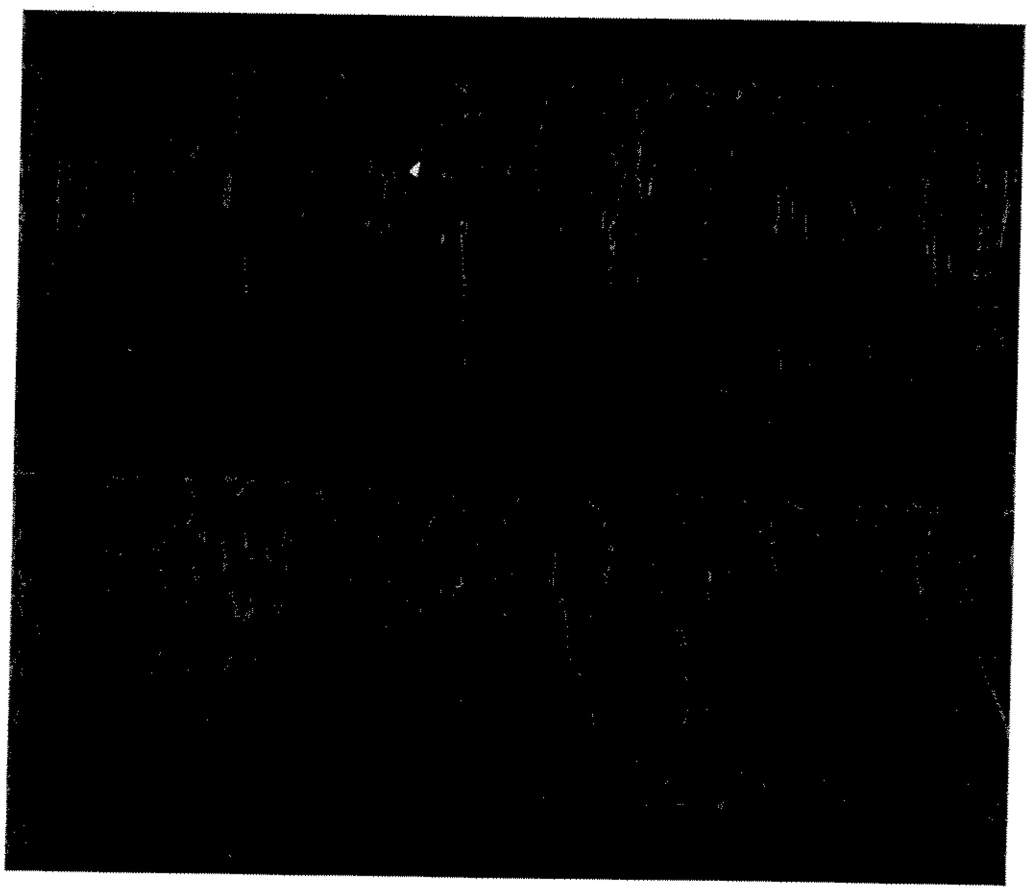


Figure 4.13 Detail of a structural wall composed of a double 3D fabric sandwich structure.

This configuration is also efficient in terms of local buckling resistance. Standard sandwich structures are weak in terms of local buckling in the sense that the skin and the core can be debonded as an effect of a compression load.

This failure mode does not exist with 3D fabric sandwich structures, since the skins are connected:

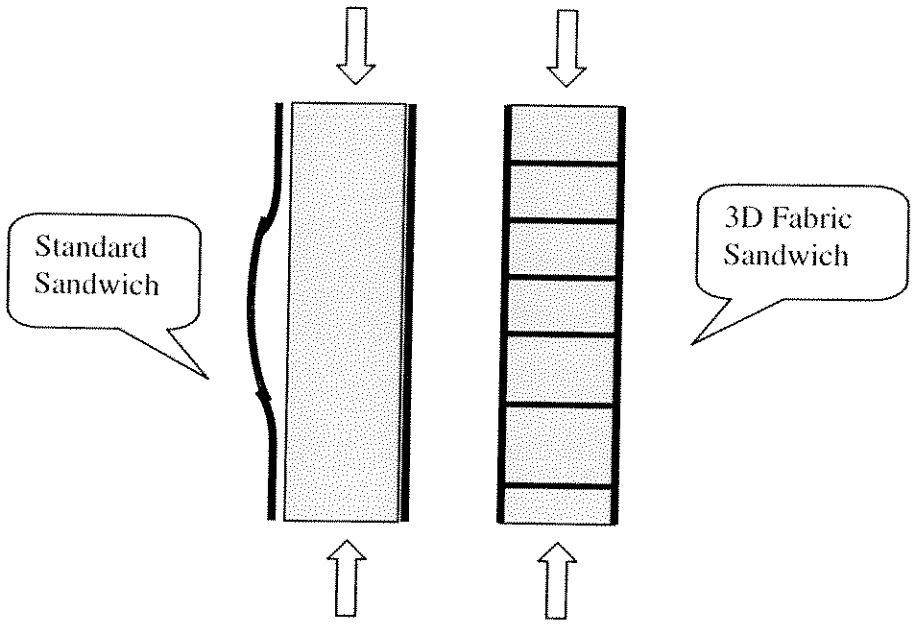


Figure 4.14 Local buckling in standard sandwich.

Since the top chord is mainly working in tension, a standard sandwich structure will be appropriate. For the two bottom chords subjected to compression and therefore, to buckling, a 3D fabric sandwich structure will be the optimum configuration in those areas of the boom where local buckling is expected.

Also the material system will be optimized along the boom. Since the highest stresses are reported at the bottom of the boom, the third bottom part of the boom will be made up of carbon fiber (67% of volume) and fiberglass (33% of volume). The third part at the middle will be composed of carbon fiber (33% of volume) and fiberglass (67% of volume). Finally, the top third part will be made up of fiberglass (100% volume). Therefore, the whole chord will have a third part in volume of carbon fiber and two thirds in volume of fiberglass.

The scheme of this optimization is represented in Figure 4.15

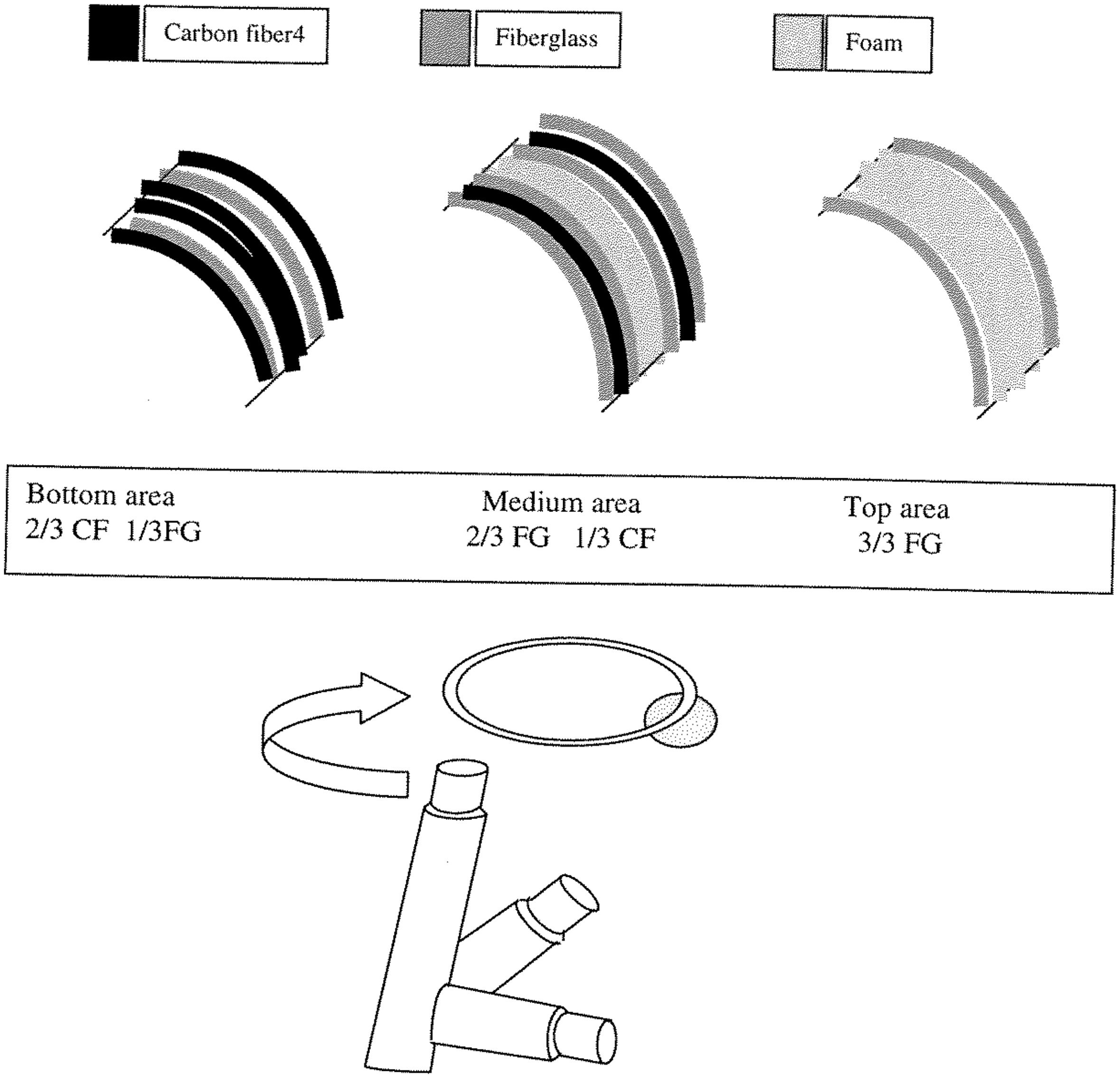


Figure 4.15 Scheme of material system and typology distribution along the boom.

5. ANALYSIS

The aim of this chapter is to show the types of analyses to carry out, in order to size the composite flare boom.

As it is explained in precedent chapters, the platform will be made up of metallic materials. Next to this zone, a non-structural ceramic coating will protect the composite structure.

The composite part will be totally structural and the ceramic coating will just isolate the inner part and it will not have any structural function. A thermo-mechanical study by means of the finite element method will be carried out in order to know the behavior of the composite flare boom subjected to both static and thermal loads.

According to the data available, dynamic and fatigue loading have demonstrated to be critical in cracking analysis reported in carbon steel flare booms.

The resin transfer processes described in this report are efficient when fabrics are used, instead of unidirectional typologies. Composite structures made of fabrics have demonstrated to be appropriate for highly structural cases, similar to the flare boom. However, buckling problems at micromechanical level have been reported as a consequence of the non-linear shape of the fibers. Therefore, a microbuclkling study must be carried out in order to assess the buckling threshold and its influence on the behavior of the flare boom when this is in operation along its lifetime.

Finally, an impact resistance study is shown in order to evaluate this parameter in our case.

5.1 THERMO-MECHANICAL ANALYSIS

The thermo-mechanical study will consist of a Finite Element Analysis applied to a flare boom.

The initial step is to build the F.E. mesh from a certain design (Figures 5.1 and 5.2.). Areas where high stress gradients are expected, must be discretized by a large number of finite elements.

A critical aspect is the election of the type of finite element. The commercial finite element software codes present a large number of finite elements for composite materials. Many of them can be used to solve in-plane and bending problems. However, the evaluation of the out-of-plane strains and stresses is complex and, usually, special techniques like substructuring and submodeling are required to catch the whole stress tensor.

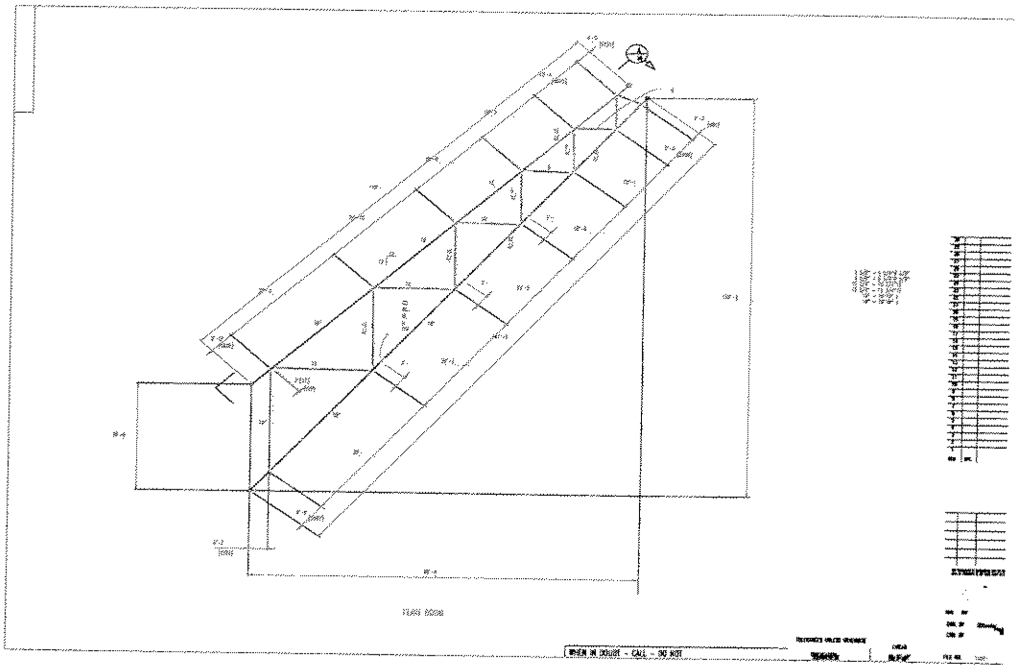


Figure 5.1 Flare boom elevation.

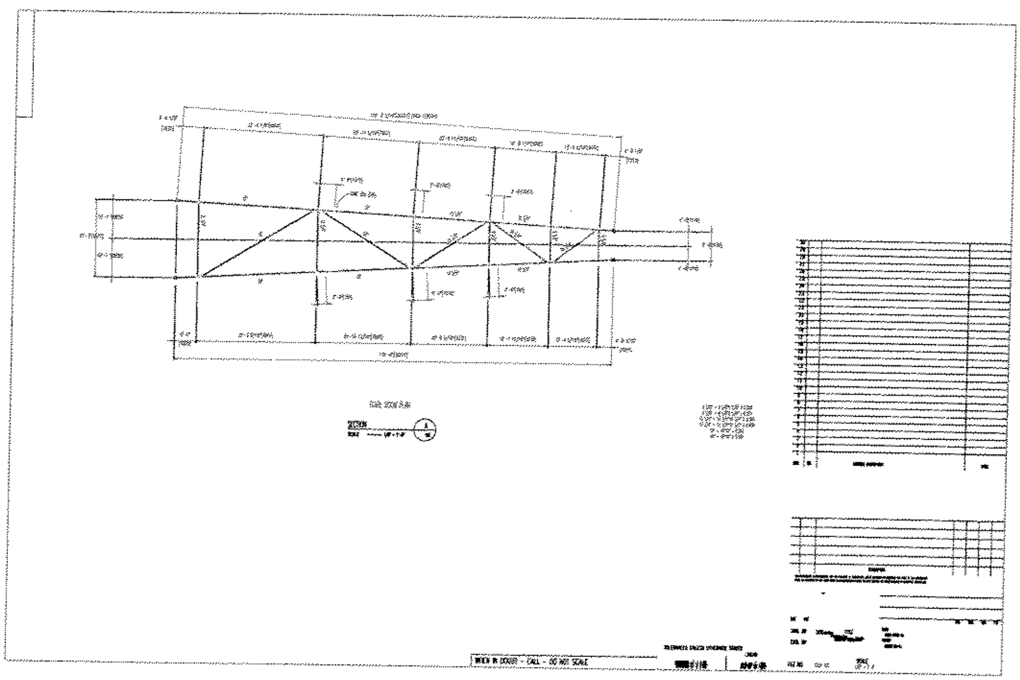


Figure 5.2 Flare Boom Plan.

Those critical areas where high interlaminar normal and shear stresses or microbuckling effects are expected, must be carefully studied.

Figure 5.3 shows a model of a substructure where peeling and shear stresses are critical.

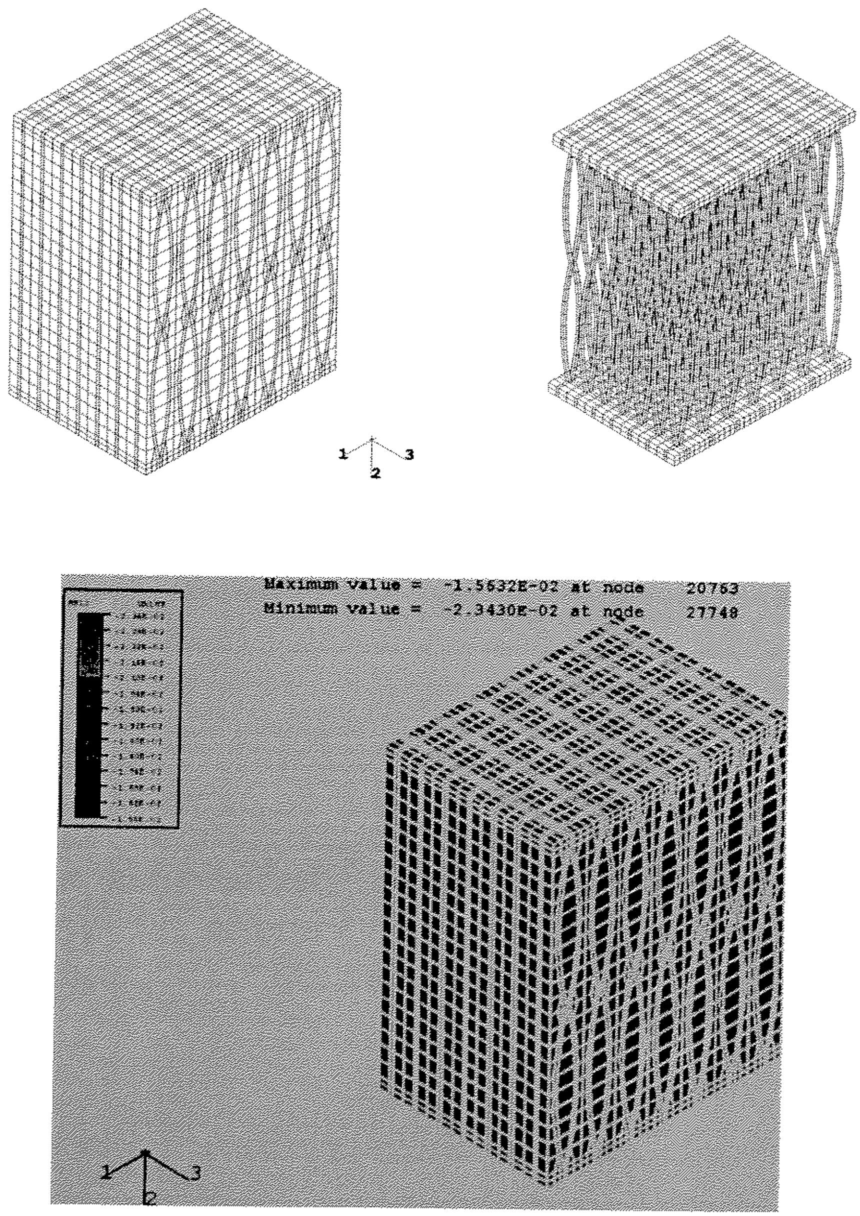


Figure 5.3 Modeling and Stress diagram of a detailed area subjected to high interlaminar normal and shear stresses.

5.2 DYNAMIC ANALYSIS

The dynamic behavior of a flare boom is essential in order to know the dynamic stiffness of the structure, the natural frequencies and finally, to assess the risks of large vibrations, problem often reported in flexible structures. This occurs when the structure does not present high enough dynamic stiffness. This fact leads to too low natural frequencies and therefore, large vibrations.

Also, those structures for which any or more of their natural frequencies are close to source frequencies, like wind, waves, engine, etc,... will have induced dynamic displacements, and therefore, large vibrations.

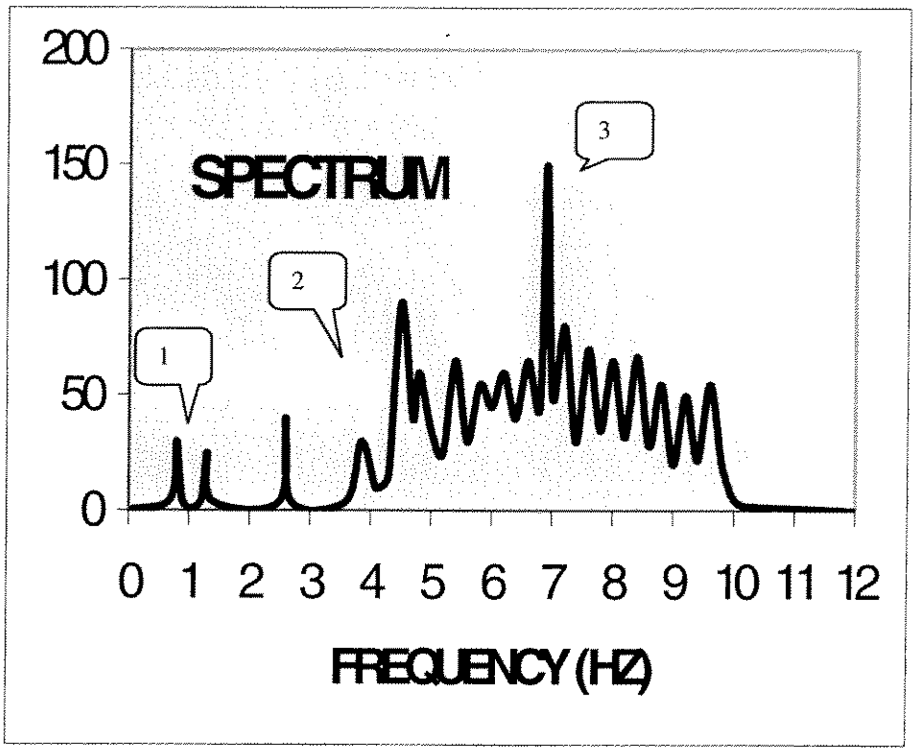


Figure 5.4 Dynamic spectrum in an offshore platform.

The spectrum in an offshore platform is represented in Figure 5.4. The area numbered 1 corresponds to the platform first and second order modes and are associated to the lowest natural frequencies of the spectrum.

The second group (number 2) of natural frequencies, and therefore critical from the dynamic stiffness point of view correspond to flare boom global modes.

Finally, the third group (number 3) is associated to the bracing first mode.

The dynamic spectrum for the current design will be similar to the one represented in Figure 5.4 except for the natural frequencies associated to the flare boom.

The natural frequency is given by the following expression:

$$f = \sqrt{(k/m)} / 2\pi$$

where k represents the stiffness of the structure and m is the mass.

According to the calculations developed along this report the stiffness of the composite flare boom will be similar to the steel one. Regarding the mass, the weight of the platform and flare tip will be the same but the weight of the rest of the structure will be much lower. It can be estimated in a conservative way, that the mass of the composite boom will be the half the mass of the steel flare boom.

Therefore, the frequency for the composite materials will be 1.4 times higher than the steel boom. This is a positive factor for the composite boom , since it means that the dynamic stiffness is higher with this new design.

Figure 5.5 represents the spectrum plot for a steel boom (black color) and a composite boom (orange color).

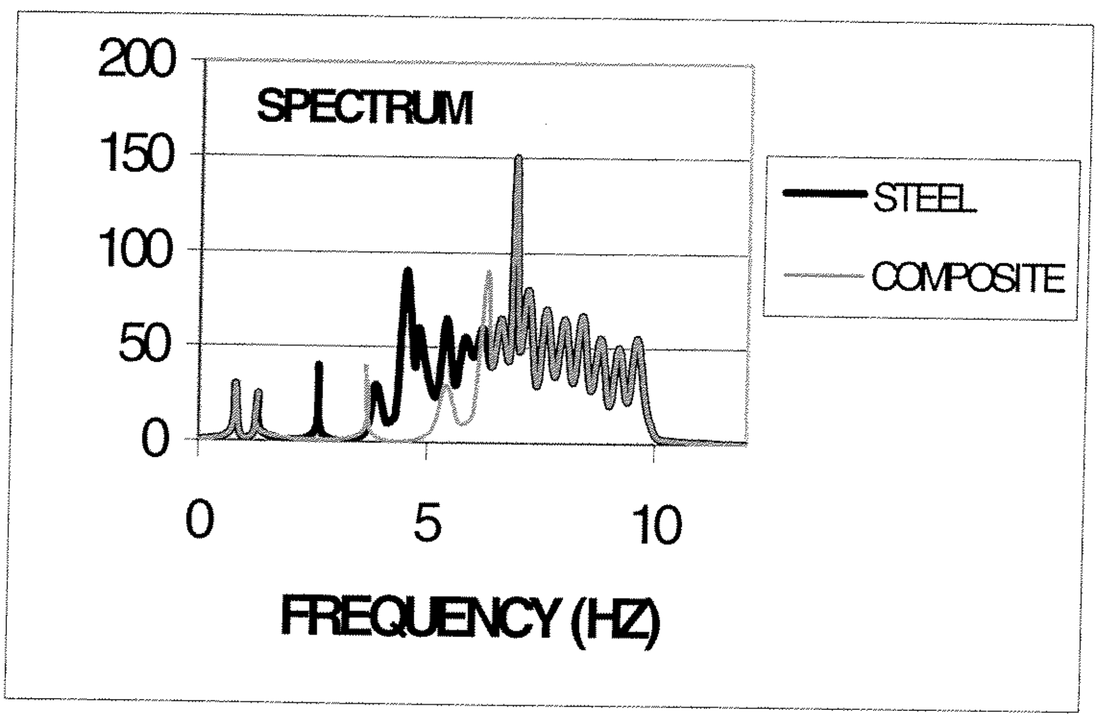


Figure 5.5 Dynamic spectrum in an off-shore platform with steel flare boom (black color) and composite flare boom (orange color).

5.3 FATIGUE

One of the most probable cause of failure in flare booms is the development of fatigue cracks. Actually, the poor weld quality in the joints combined with the wind loads are considered a major problem of the steel flare boom behavior in terms of fatigue life.

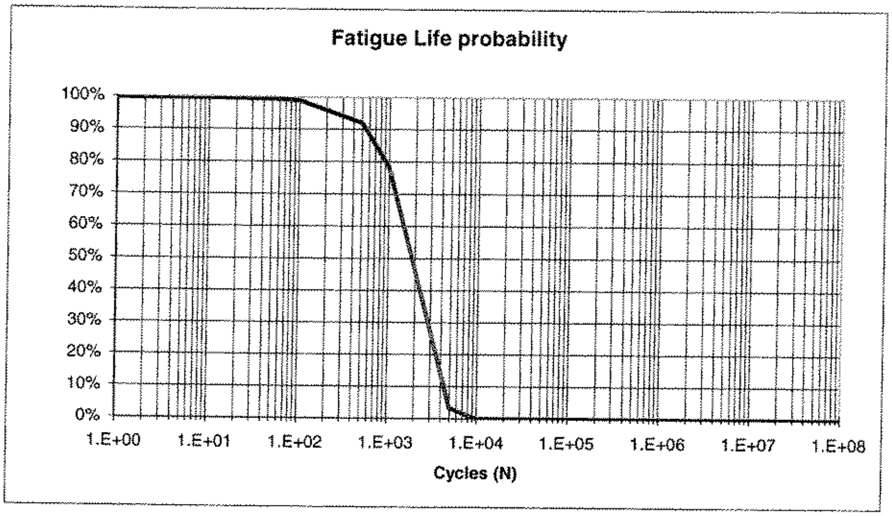


Figure 5.6 Fatigue Life Probability of a unidirectional fiberglass/polyester composite material (60% volume fiber) with σ = 1300 MPa.

A complete fatigue study will be carried out for the composite flare boom in terms of fatigue behavior. Both laminates: [0] and the fabric [0/90] will be analyzed.

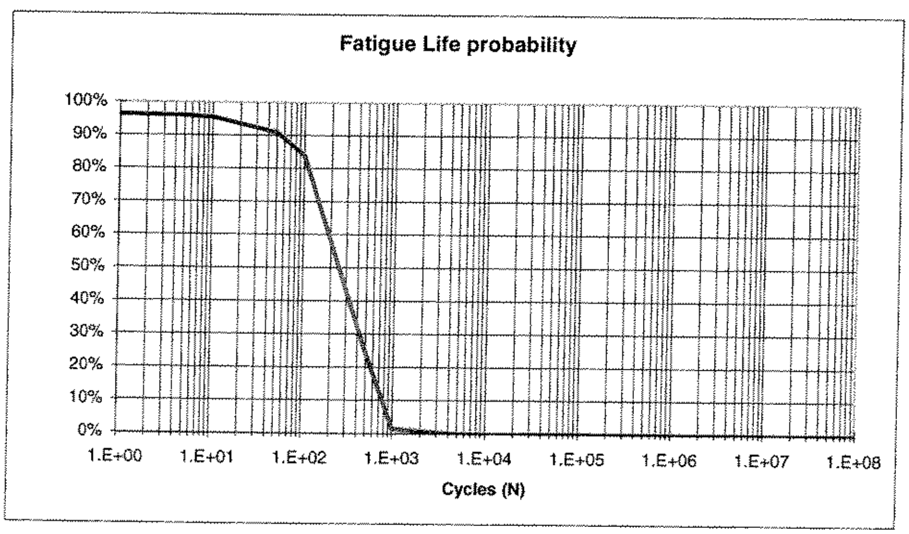


Figure 5.7 Fatigue Life Probability of a unidirectional fiberglass/polyester composite material (60% volume fiber) with σ = 1000 MPa.

For the laminate fiberglass/polyester [0], the fatigue life probability for two stresses (1300 and 1000 MPa) , the residual strength probability and S/N curve are represented in Figures 5.6, 5.7, 5.8 and 5.9, respectively.

By means of these analyses, the allowable values in terms of fatigue behavior can be drawn. These parameters will be used in the fatigue structural analysis of the flare boom.

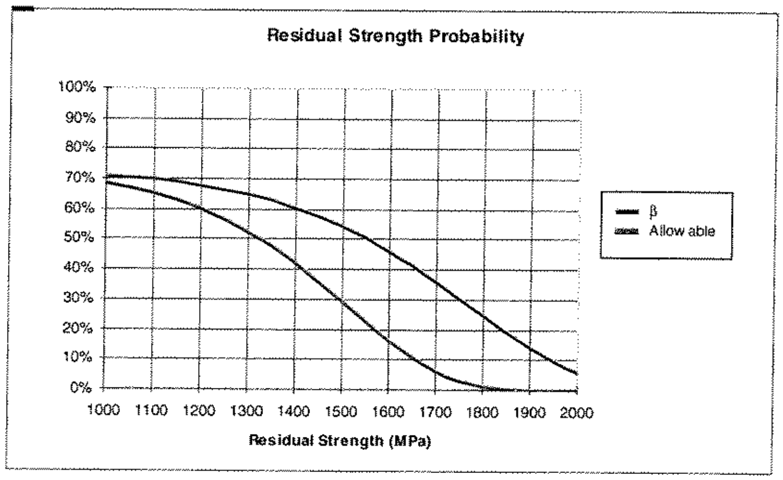


Figure 5.8 Residual Strength Probability of a unidirectional fiberglass/polyester composite material (60% volume fiber) with σ = 330 MPa.

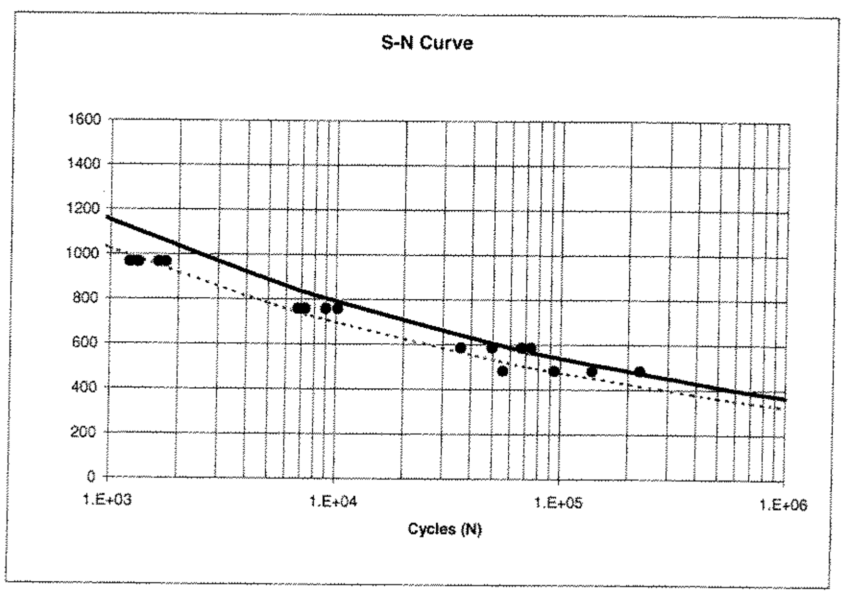


Figure 5.9 S/N Curve of a unidirectional fiberglass/polyester composite material (60% volume fiber)

For the laminate fiberglass/polyester [0/90], the fatigue life probability for two stresses (300 and 250 MPa) , the residual strength probability and S/N curve are represented in Figures 5.10, 5.11, 5.12 and 5.13, respectively.

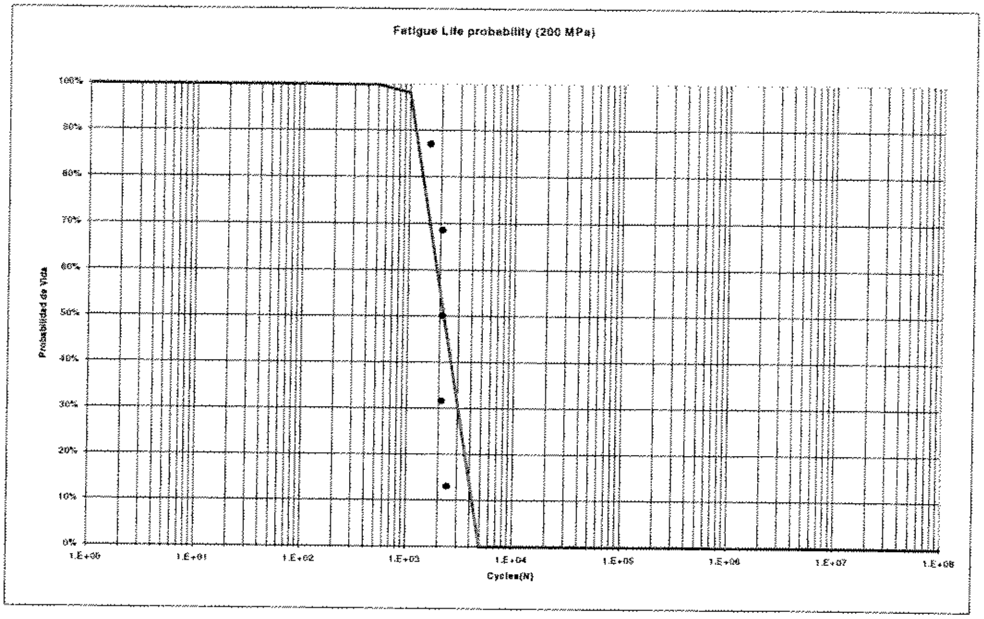


Figure 5.10 Fatigue Life Probability of a fiberglass/polyester composite material fabric (60% volume fiber) with σ = 300 MPa.

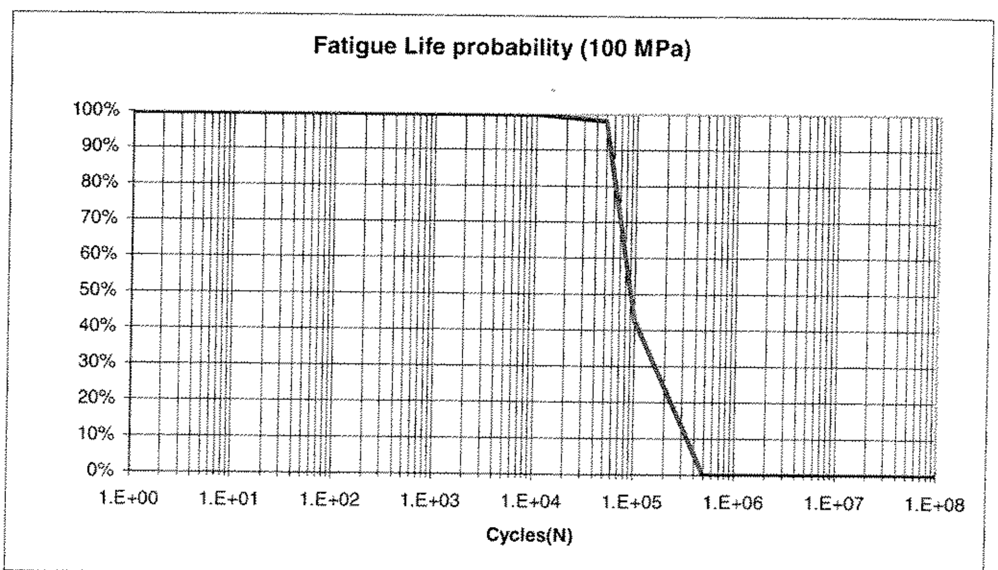


Figure 5.11 Fatigue Life Probability of a fiberglass/polyester composite material fabric (60% volume fiber) with σ = 250 MPa.

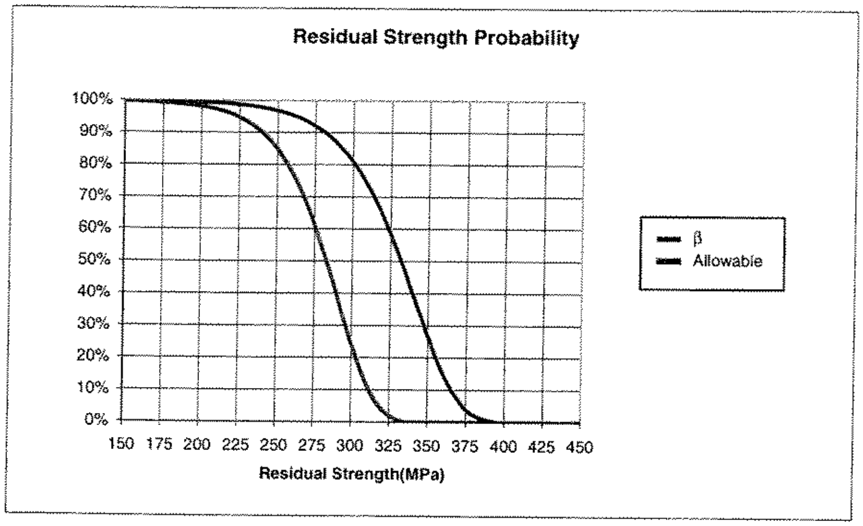


Figure 5.12 Residual Strength Probability of a fiberglass/polyester composite material fabric (60% volume fiber) with σ = 40 MPa.

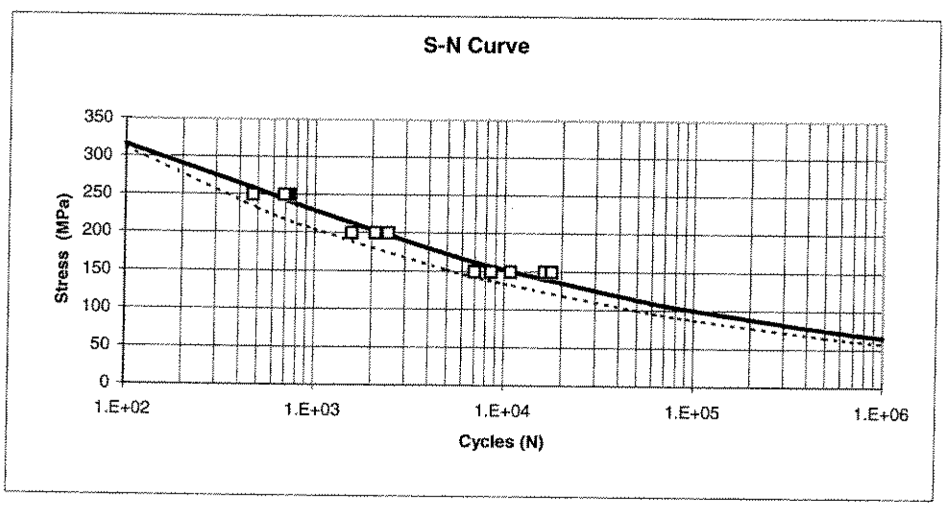


Figure 5.13 S/N Curve of a fiberglass/polyester composite material fabric (60% volume fiber).

If the graphics represented above are compared to the steel curves, the main conclusion to be drawn is that composite materials exhibit higher fatigue strength that the standard carbon steel.

However, the current design can still be optimized in terms of fatigue by the implementation of carbon fiber. As it has been mentioned in Chapter 3, carbon fiber is a suitable material system to be incorporated here due, basically, to stiffness requirements.

Carbon fiber is one of the most outstanding material system in terms of fatigue behavior. Apart from being a very strong material in static conditions, the slope of the curve S/N is almost horizontal. In other words, the strength after 1 million cycles is about the same as the static strength. This concept can be visualized in the Figure 5.14:

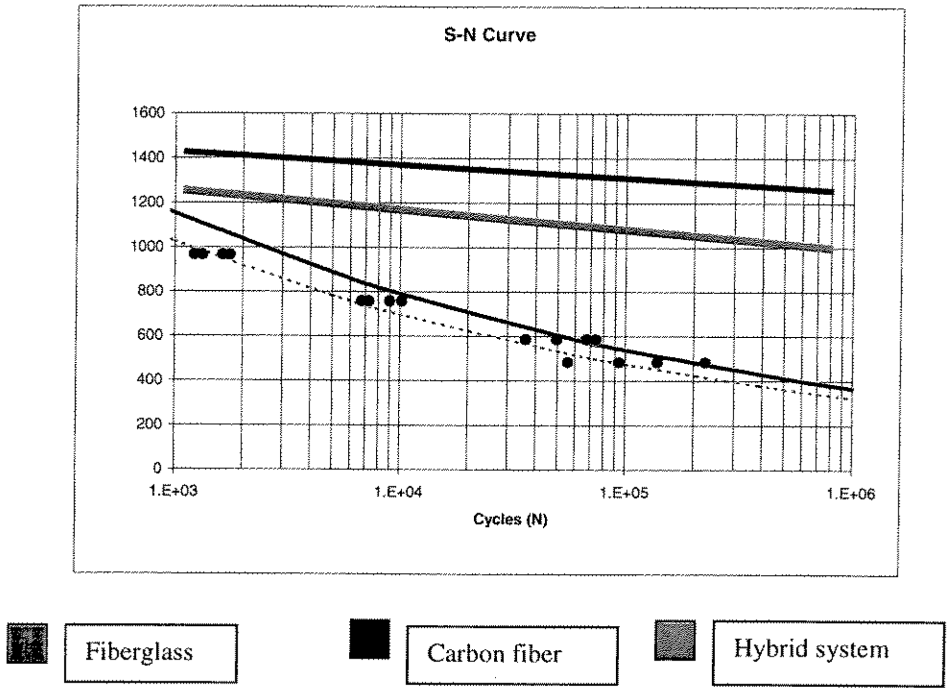


Figure 5.14 S/N Curve of a hybrid system unidirectional carbon fiber (67%) and fiberglass (33%) composite material (60% volume fiber).

The material system represented in Figure 5.14 is the one selected for the boom bottom, where the stress level is the highest. For the medium part, the carbon fiber will be only one third of the volume and the fiberglass, the other two thirds. In this case, the final S/N curve (red color) will be closer the fiberglass (blue color) than the carbon fiber (black color). Finally, the top third boom part will be 100% fiberglass. Therefore, the final S/N curve will coincide with fiberglass (blue color).

The fatigue design, analysis and optimization are one of the most critical processes to be performed from the strength point of view. Once the fatigue parameters are calculated, an accurate finite element analysis must be carried out in order to assure that the allowable data are lower that the stress in the worst conditions.

Design concepts also must be applied in order to eliminate the fatigue as a probable failure case. The joints between chords and transverse braces must be accurately sized. Also, the piling sequence must be determined in order to avoid trends to delamination, which are critical when the structure is exposed to fatigue loads.

5.4 FAILURE ANALYSIS

Along this report, several failure modes like global and local buckling have been reported. However, there is a number of failure modes exhibited in a composite structure like a flare boom :

- In-plane modes:
  - Fiber breakage
  - Matrix cracking
  - Fiber-Matrix Debonding

- Out-of-Plane modes:
  - Delamination due to shear stresses
  - Delamination due to peeling stresses

- -Buckling related modes:
  - Global buckling
  - Local buckling (chord buckling)
  - Local buckling (chord wall buckling)
  - Microbuckling

In-plane and out-of-plane modes can be obtained by applying appropriate finite elements and meshing the structure in a suitable way. Special attention must be paid in the simulation of out-of-plane modes and the application of an accurate failure criterion to obtain the delamination threshold. Global and Local buckling can also be studied by solving the eigenvalue and eigenvector problem.

Figure. 5.15 3D Micromechanical model for microbuckling analysis

According to our experience in the study of composite structures similar to the flare boom: highly structural parts, existence of compression loads and use of fabrics, microbuckling must be accurate analyzed in order to obtain the critical microbuckling stress. If this threshold stress is lower than the other modes above described, this typology (thickness, fiber size, orientations, etc) must be redesigned. If the critical microbuckling stress is higher than the other modes, the fibers will withstand the compression load in spite of the curved shapes that the fabric itself imposes.

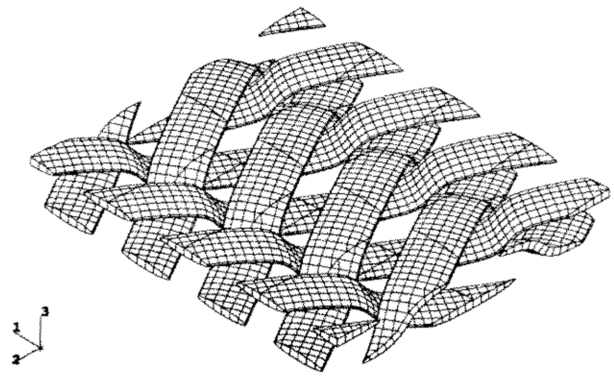


Figure. 5.16 2D Micromechanical model for microbuckling analysis

In order to analyze a certain substructure in terms of microbuckling failure, a micromechanical model must be built.

There are several ways to perform a micromechanical model to carry out a microbuckling analysis:

- 3D model
- 2D model
- Model using substructuring techniques
- Model using submodeling techniques

These four technologies have been represented in Figures 5.15, 5.16, 5.17 and 5.18 respectively.

The 3D model is recommended for those analyses where very exact solutions are required. This technique is very expensive in terms of calculation, since the number of the degrees of freedom is very high, but according to our experience the results are very close to the experimental data (errors lower than 5%).

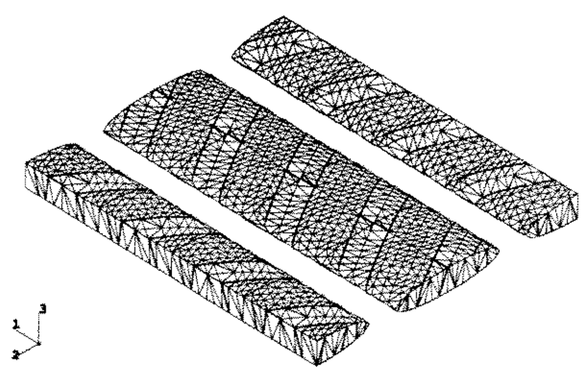


Figure. 5.17 Micromechanical model for microbuckling analysis by using substructures techniques

The 2D model is usually applied for those cases where the critical microbuckling load must be obtained with certain accuracy (errors about 15-25%). The CPU time is much lower than the 3D analysis.

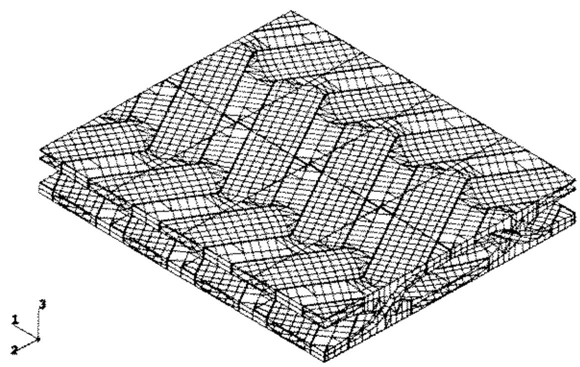


Figure 5.18 3D Micromechanical model for microbuckling analysis by using substructures techniques.

Substructuring and Submodeling techiques are used when a portion of the structure is repeated many times. These types of analyses are very efficient for many composite structures calculation, where the fiber level study is needed. Meshing a substructure or a submodel just once, the global model is built automatically. High saving time is reported in comparison with the typical local model.

5.5 IMPACT RESISTANCE

An impact resistance study must be carried out, due to the fact that composite materials present low impact resistance in low energy impact problems.

Explicit techniques are recommended to carry out impact studies on composite structures.

The typologies described along this report present high impact resistance in comparison with the traditional composite materials.

Usually, laminated composite materials exhibit a trend to delaminate when an impact load is applied. This is due to the fact that the strength in the thickness direction is quite low. Fabrics and 3D fabric sandwich structures present higher impact resistance.

The micromechanical models shown in Section 5.5 can be used for impact studies at a micromechanical level. Once we know the resistance at a fiber level, a global structural analysis can be performed.

Figure 5.19 shows the force-displacement graphic which represent the results from an impact studies. The amount of energy absorbed is very high. Not only is a high peak for low strains reported, but a steady force after the first impact is also obtained up to high strain levels.

The graphics at the top right part of Figure 5.19 show the stress plot in the micromechanical level. The disposition of the fibers is essential for the stability of the structure. Initial failures are reported in the matrix, as expected.

Also, the other models described in Section 5.4 can be applied for impact studies. For the flare boom case, any type of impact must be absorbed without any structural damage. Apart from micromechanical analyses, where the material behavior is studied, other calculations must be done in order to assure the reliability of the flare boom in terms of impact resistance.

The chords, manufactured by resin transfer technologies, are expected to behave properly in terms of impact resistance. In those areas of the flare boom where an impact load is expected, a 3D fabric sandwich structure can be implemented. This typology shows an outstanding behavior in terms of impact resistance, due to the fact that the skins are connected through the thickness direction by means of piles.

Pultruded transverse braces show also a good impact resistance, as far as this aspect is considered in the manufacturing process. Obviously, though the zero degree layer compose the major part of the thickness, another typology with high transverse properties must be included in order to meet the impact requirements.

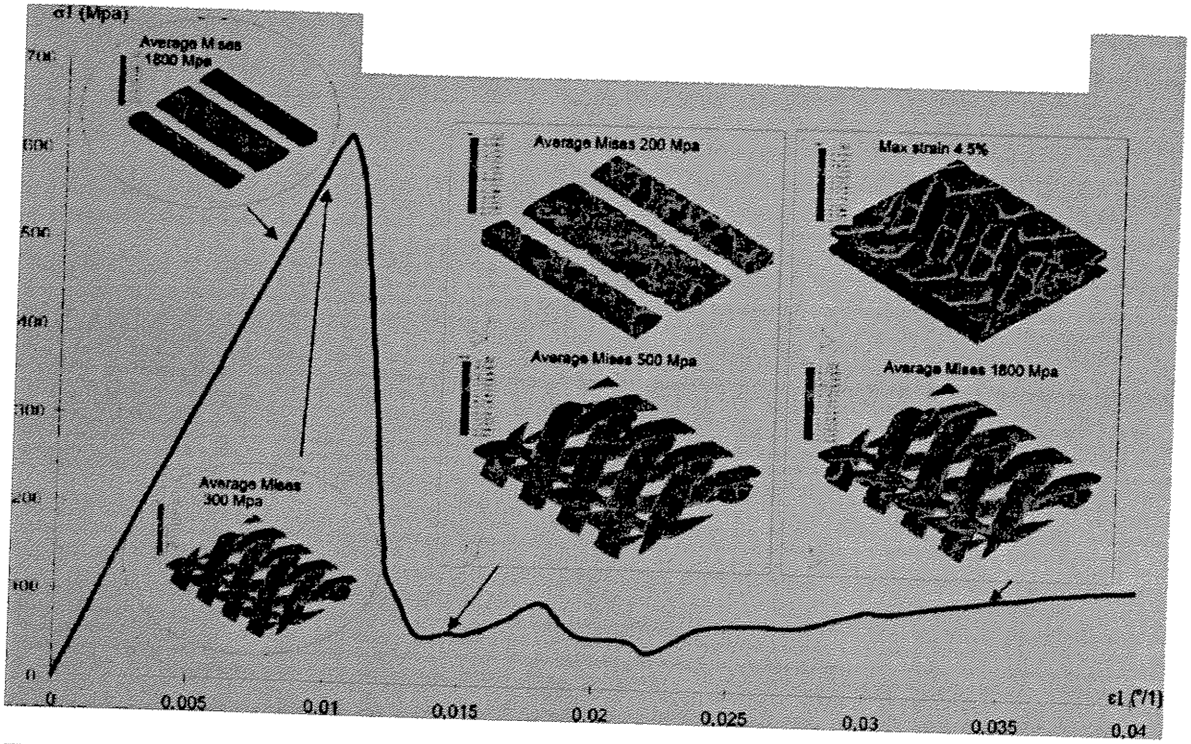


Figure 5.19 Force-displacement curve showing impact behavior of a composite fabric.

Special attention must be paid to the design of the joints: chord-transverse braces. As it was above explained, this critical area will be designed accurately in terms of static, dynamic, fatigue and impact resistance due to the fact that the diagonal braces have been suppressed and a concentration stress phenomenon is expected.

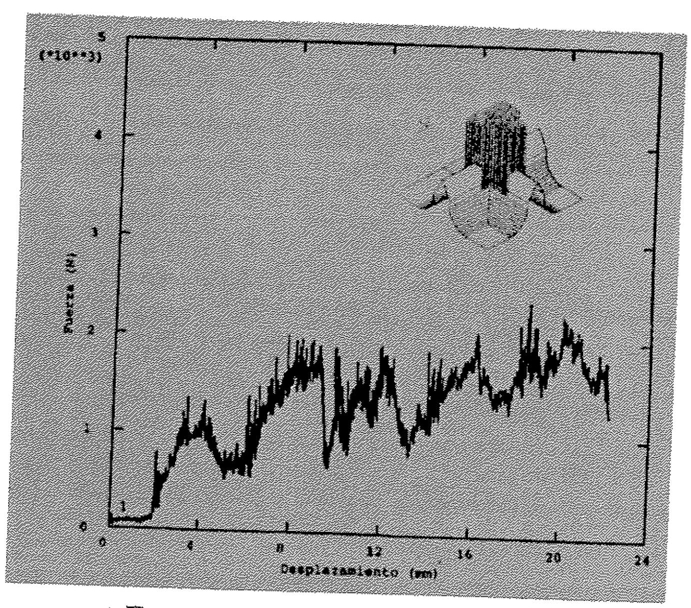


Figure 5.20. Displacement-Force Curve for a T joint.

Figures 5.20 and 5.21 show the force-displacement plot of a T and a cross sections subject to an impact load.

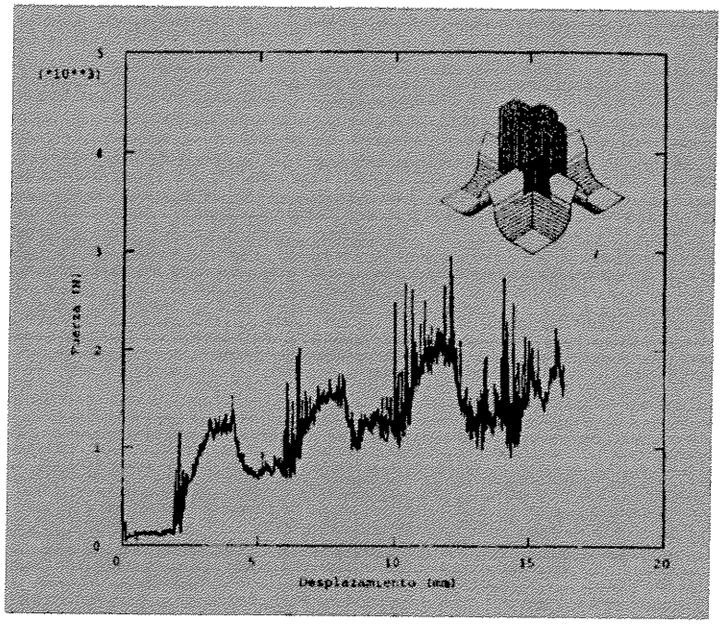


Figure 5.21. Displacement-Force Curve for a cross joint.

Both graphics show an outstanding behavior in terms of impact behavior, since the load is steadily maintained along the displacement axis. Fabrics and unidirectional laminates were used in this study. Figure 5.22 show the deformed shape of a T joint, very similar to the one between the chord and the transverse brace in the flare boom.

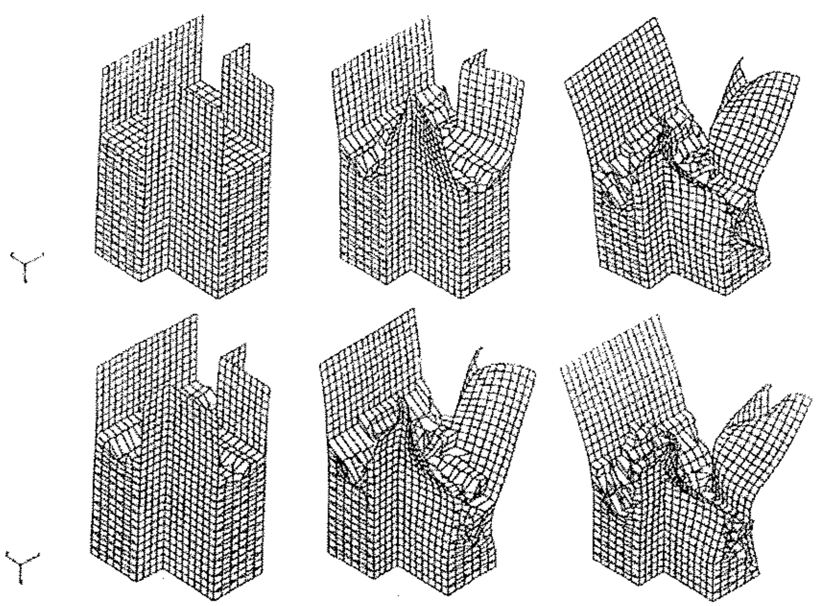


Figure 5.22 Progressive deformation of a T section subjected to an impact load.

6. CONCLUSIONS

The conclusions of the work done up to now can be drawn from the following example:

Let us compare a standard flare boom for a typical offshore platform from the Gulf of Mexico with this new design.

MECHANICAL ANALYSIS

STANDARD FLARE BOOM:

Boom length: 150 ft

Weight

- Chords (3) : 28,347 lb
- Transverse braces: 16,841 lb
- Diagonal braces: 30,629 lb
- **Total boom weight: 75,817 lb**
- Platform weight: 10,000 lb
- Flare tip: 2,000 lb
- Others; 3,000 lb

Surface expose to wind: 337,591 in^2

Wind Velocity: 120 m/h
(ANSI/ASCI7)

Deflection: 1ft 5 in
Safety margin: 3

COMPOSITE FLARE BOOM:

Boom length: 150 ft

Weight

Chords (3) : 7,087 lb
Transverse braces: 4,211 lb
Diagonal braces: 0 lb
Total boom weight: 11,298 lb
Platform weight: 10,000 lb
Flare tip: 2,000 lb
Others: 3,000 lb

Surface exposed to wind: 222,810 in^2

Wind Velocity: 120 m/h
(ANSI/ASCI7)

Deflection: 1ft 3 in
Safety margin: 5

COST ANALYSIS

STANDARD FLARE BOOM:

Raw Materials

$2/lb X 75,817 lb =	$151,634
Coating	
$0.8 X 75,817 lb =	$ 60,654
Total cost	**$212,288**

COMPOSITE FLARE BOOM:

Raw Materials

Pultruded transverse braces	
$5/lb X 4,211 lb =	$21,055
Chords	
$3/lb X 4,725 lb =	$14,175
$8/lb X 2,362 lb =	$18,896
RTM Manufacturing and Assembly	
$15/lb X 7,087 lb =	$106,305
RTM Mould	
$100,000/5 =	$20,000
Adhesives	
$30/lb X 180 lb =	$5,400
Foam	
$25/lb X 30 lb =	$750
Coating	
$5/ft^2 X 2,063 ft^2 =	$10,315
Total cost	**$196,896**

7. ADDITIONAL TECHNICAL INPUT REQUIRED

a) Thermal Requirements

- Flow (MMSCFD)

b) Mechanical Requirements

- Wind Velocity (m/h)
- Weight of the rest of the elements (stairs, handrails,...)
- Definition of gas conduction from deck to flare tip
- Safety margin
- Maximum deflection
- Minimum natural frequency
- Fatigue life

c) Manufacturing Requirements

- Costs related to Resin Transfer technologies (mould, manufacturing,...)
- Assembly Cost

d) Installation Requirements

- Cost of Transportation
- Cost of installation

8. REFERENCES

1. L. E. Owen, W. Rothrock "Cantilever Flare Boom Design for Offshore Platform", OTC 2482

2. Y. J. Doucet "Vibration Monitoring of a Flare Boom", OTC 5523

3. E. R. G. Bell, D. G. Morgan "Repair and Analysis of Cracking in the Murchison Flare Boom" OTC 5814

4. Journal Fuel Technology Management, 3/98

5. API RP 521 "Selection of Disposal Systems", 1997

6. L. Owen, H. Huang " Gas Flare Stack Design for Offshore Production Facilities", Petroleum Engineer, August, 1975

7. A. Nordhous, Y. J. Doucet "Vibration Monitoring of the Heimdal Flare Boom", Norges Sivilingeniorers Forening, April 1986

8. BS 1800: Part 1. "Lattice Towers and Mats', 1986

9. E. Smith, M. Solberg, O. Skalmeraas "Stochastic Dynamic Analysis of Steel Truss Towers to Wind Gustiness", Proceedings of 3rd OMAE Symposium, 1984

10. AMOCO Technical Information, 1998

11. KALDAIR Technical Information, 1998

12. S.W. Tsai, A. Miravete, "Analysis and Design of Composite Materials" edited by Ed. Reverte, Barcelona, Spain, 1988

13. R. Y. Kim, A. Miravete "Testing of Composite Materials", Edited by University of Zaragoza, Spain, 1992

14. J.N. Reddy, A. Miravete "Practical Analysis of Laminated Composite Materials" edited by CRC Publishers, USA, 1995

15. A. Miravete "- Optimization of Composite Structures" edited by Woodhead Publishing, UK, 1996

16. A. Miravete, E. Larrodé, L. Castejón "Crash Behaviour of components for the automotive industry: Background (Part 1)" Engineering Plastics, edited by Rapra Technology Ltd., UK, 1996

17. E. Larrodé, A. Miravete, L. Castejón "Analysis of Large Structures for Ground Transportation Applications" Proceedings of 29th International Symposium on Automotive Technology & Automation (ISATA), Florence, Italy, 1996

18. J.J. Alba ., M. A. Jimenez ., A. Miravete "New Sandwich" Structures Conformed from Three Dimensional Fabrics" Materiales de Construcción, Vol. 46, n† 241, Spain, 1996

19. K. Drechsler, J. Brandt, E. Larrode, A. Miravete "Energy Absorption Behavior of 3D-Woven Sandwich Structure" Proceedings of Tenth International Conference on Composite Materials (ICCM-10), edited by University of Vancouver, Canada, 1995

20. A. Miravete "Optimisation of a Full Composite Isotherm Trailer Structure" Journal of Composite Structures, UK, 1996